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SPACE STRUCTURE OF HADRONS AND SOFT PROCESSES

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Introduction

All the recent conceptions of the strong interactions are based on the notion of quarks[1], which appeared in the early sixties as a mathematical expression of the SU(3) symmetry properties of hadrons. Since then it had gone through a long way of evolution. Quarks as objects inside the hadrons appeared first in the "classical" models of constituent quarks [2-5]. Further, if turned out, that in the framework of the quark model not only the hadron spectra can be obtained, but - using the impulse approximation - hadron-hadron collision processes at high energies can also be handled[6-8]. The investigation of hard processes (such as deep inelastic scatterings of electrons, muons and neutrino on nucleons, $\mu^+\mu^-$ production with large effective masses in hadron collisions, e^+e^- annihilation into hadrons) led also to the quark structure of hadrons. Indeed, the quantitative description of these processes on the basis of the parton hypothesis required the introduction of point-like objects, the symmetry properties of which coincided with those of the constituent quarks.

Under these circumstances it was quite natural to try to observe quarks. However, long and tedious experimental work led to no results. This fact suggested the idea that the absence of direct experimental evidence of the quarks in due to the character of their interactions.

At last, we seem now to dispose of such a theory of strong interactions, which contains the quark picture, introducing in a natural way the required new quantum number, the colour. QCD being an asymptotically free theory, i.e. a theory in which interactions at short distances (at large momentum transfers) are small, gives a description of hard processes which is in accordance with the predictions of the parton model. At large distances the interaction increases and might lead to the confinement of quarks.

At the same time, this means, that considering soft processes one has to deal with the problems connected with strong interactions. It is reasonable therefore to describe soft processes in a different, semi-phenomenological way, which is in agreement with the experimental data and at the same time does not contradict the theory, moreover, gives some indications to the character of the confinement. Hence, one can hope that even if the problem of the confinement will be solved the results of this semi-phenomenological description remain valid.

In the following we present such an approach, which enables us to handle soft processes. This is based on a hadron picture due to which the baryons (and mesons) are formed by three (or respectively, two) constituent quarks which are separated in space, i.e. the sizes of quarks are much less than those of the hadrons[9,10]. The presence of just three or two discrete objects in a hadron can be reconciled with the parton picture assuming that a fast moving hadron is a system of three (or two) spatially separated clouds of partons, each containing a valence quark, a sea of quark-antiquark pairs and gluons. In the case of such a hadron, which, like a nucleus, is characterized by two different sizes, the impulse approximation can be applied for hadron collisions at high energies.

There are several experimental facts which seem to support this hadron picture. In elastic hadron-hadron scattering processes at high energies the shrinkage of the diffractional cone was observed. The parameter α'_P (the slope of the pomeron) characterizing the shrinkage is small in comparison with the slope of the diffractional cone itself. This is an indication of the existence of a second, small characteristic size inside the hadron (besides the hadron's own radius), which, assuming the constituent quark model, is the small radius of the constituent quark[9].

Good proofs for the picture of hadrons containing quasi-free constituent quarks are given by the comparison of the experimental data and the theoretical predictions in hadron-nucleus interactions at high energies[11-16] and in multiparticle production processes. We will come to them later.

The considered hadron picture might be a simplified one. Still, apart from describing well the soft processes at high energies, it gives a possibility to connect the results of investigations in hard processes[17,18] with the "old" quark physics[2,6-8,19].

Not before long on the basis of investigations on gluonium states[20] some theoretical arguments have been expressed in favour of such a double structure of hadrons[21]. Due to them, the confinement region of gluonium states might be much less than that of the quarks, i.e. the "coat" of the constituent quarks is consisting mainly of gluons.

The quark structure of hadrons

Let us remind the well-known arguments supporting the impulse approximation in hadron collision processes at high energies. Comparing theoretical predictions with the experimental data, it turned out, that the processes

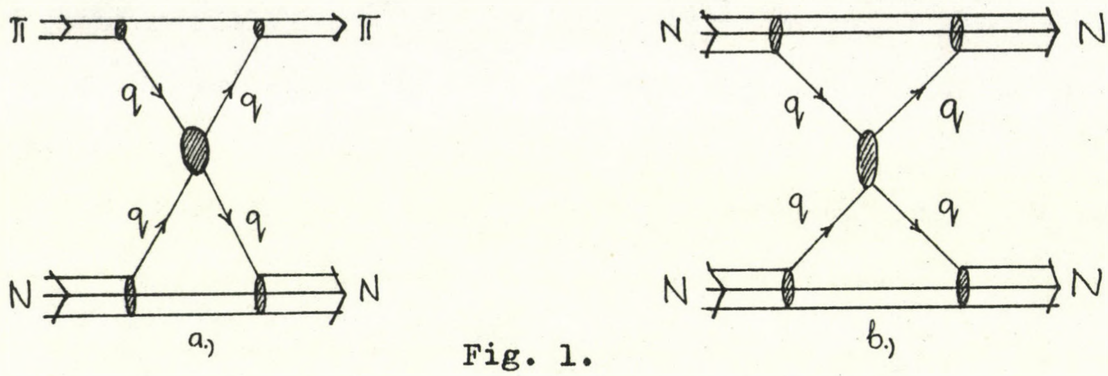


Fig. 1.

describe sufficiently well the ratio of the total cross sections in NN and πN scattering/6-8/

$$\frac{\sigma_{tot}(NN)}{\sigma_{tot}(\pi N)} = \frac{3}{2} \qquad (1)$$

as well as the decrease of the elastic pp-cross-section with the increase of the momentum transfer/7/

$$\frac{d\sigma_{pp\to pp}(t)}{dt} \sim F_p^4(t), \qquad (2)$$

where $F_p(t)$ is the proton form-factor.

Accepting the hadron picture with two radii, we assume, that hadrons are similar to light nuclei: the meson, consisting of a quark and an antiquark sufficiently far from each other reminds the deuteron while the baryon contains three consituent quarks in the same way as H_3 or He_3 is build up. The constituent quarks are surrounded by their "coat" of virtual particles. The radius of this "coat" is in fact the radius of the constituent quark. The mean distances between the constituent quarks determine the size of the hadron[9-10,22].

The radius of the constituent quark can be estimated from the total hadron-hadron cross-section, which, as it follows from Fig.1, can be expressed in terms of the total quark-quark cross-section. At moderately high energies $\sigma_{tot}(qq) \simeq 4{,}5$ mb. Assuming, that the total quark-quark cross-section is determined by the geometrical sizes of the colliding quarks $\sigma_{tot}(qq) \simeq 2\pi(2r_q)^2$ we obtain

$$r_q^2 \simeq 0{,}5\ \mathrm{GeV}^{-2} .$$

There is another way of obtaining the radius of the constituent quark in the framework of the parton hypothesis. Without going into the details, we give here only the results: due to the latest experimental result at Fermilab

$$r_q^2 \simeq 3\alpha'_p \simeq 0{,}45\ \mathrm{GeV}^{-2}.$$

Hence, having $R_h^2 \simeq 17\ \mathrm{GeV}^{-2}$,

$$r_q^2/R_h^2 \simeq 1/30$$

We consider here, naturally, coloured quarks. Since the quark confinement is due to the colour forces, we are bound to accept the following hadron picture. (In the following we consider a nucleon). At large momenta (but $P < 10^8$ GeV/c) the nucleon contains three clouds of quarks-partons (Fig. 2a).

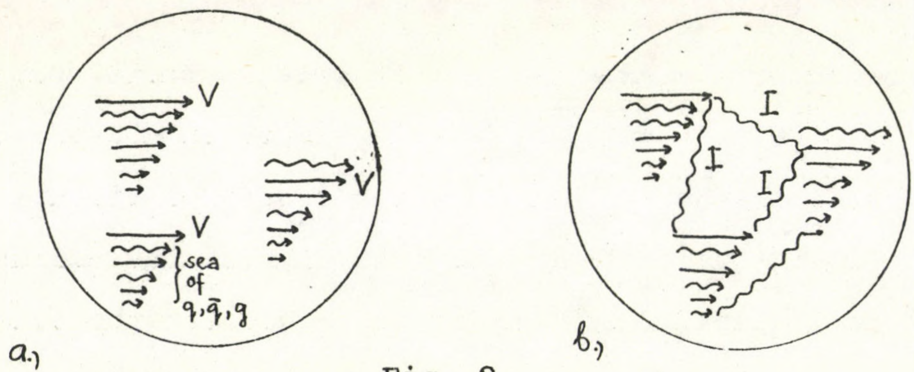


Fig. 2.

Each of the clouds contains a coloured quark-parton which carries the quantum numbers of the constituent quark, and a sea of quark-antiquark pairs and gluons, which is colourless and has zero quantum numbers. The gluon interaction which keeps the constituent quarks inside the hadrons is taking place between the fast parton components/23/(I).The gluon exchange is inprobable between the partons carrying a relatively small fraction of the momentum(II).

The transverse dimension of a cloud increases with the energy as $\sqrt{\alpha'_p \ln P/P_0}$, $P_0 \sim 10$ GeV/c.Up to $P \ll 10^8$ GeV/c r_q remains essentially less than R_h , and, practically, the three (or in the case of a meson, two) clouds do not overlap. When a fast hadron collides with the target, only one of the constituent quarks paricipates in the interaction; the other constituent quarks, or quark-parton clouds, remain spectators. The situation is different in the case of a hadron-nucleus interaction, i.e. when the target in large, and not only one, but two or three constituent quarks of the incident hadron can interact. We will come to this question later. As soon as $r_q^2 \ll R_h^2$, repeated collisions of the quarks are not probable. The interaction with the target is due to the slow components of the partons (a parton carrying energy E needs a time of the order of $\tau \sim \frac{E}{\mu^2}$ to interact). The quark-parton cloud the slow component of which participated in the interaction breaks into partons. These partons then, interacting with each other, obtain their own "coats" and become constituent quarks, giving rise to the production of new particles (Fig. 3).

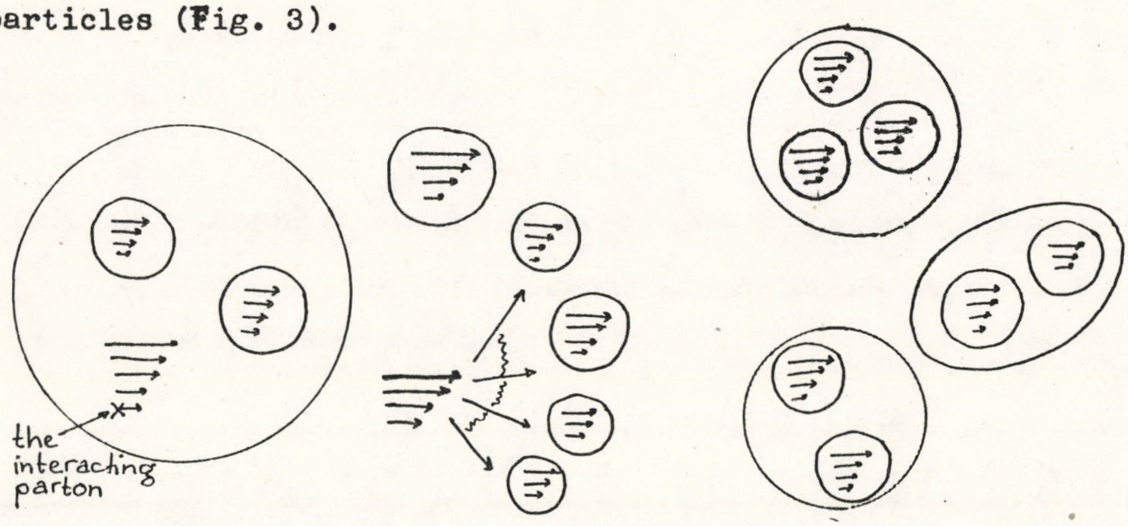


Fig. 3.

The approach we are presenting deals in fact with the second and the third steps: the interactions of the partons and the gluons with each other which lead to the formation of constituent quarks, and the transition of these constituents into hadrons (mesons, baryons, meson and baryon resonances) in such a way that the set of hadron states corresponds to the states of the constituent quarks in the multiperipheral ladder. This approach is by no means the only possibility to handle the problem of the quark-hadron transfer. Very popular is recently the recombination model /41-45/. Here the recombination of the quark-partons into the observable hadrons is investigated neglecting the intermediate states of this process like constituent quarks and resonances. This approach leads to an impressive agreement between the π^+/π^- ratio in proton collisions and the ratio of the proton structure functions $u(x)/d(x)$ measured in deep inelastic lepton-nucleon interactions. It is not clear, however, how the obtained pion spectra are connected with the spectra of resonances (ρ, ω etc.) the decays of which are relevant from the point of wiew of the spectra of long living particles.

In /39,40/ the recombination of the quark-partons into hadrons is investigated introducing in the last step the "dressed" quarks (i.e., in our language, constituent quarks). That means, an attempt is made to calculate the distribution of the constituent quarks. To find such a distribution would be of great importance; however, it seems to be also rather complicated. There exist some experimental facts indicating that the collective interactions of a large number of quarks-partons and gluons are relevant from the point of view of the formation of the constituent quark spectra in hadron collisions. In other words, the coherence of the initial state of partons and gluons plays an important role.

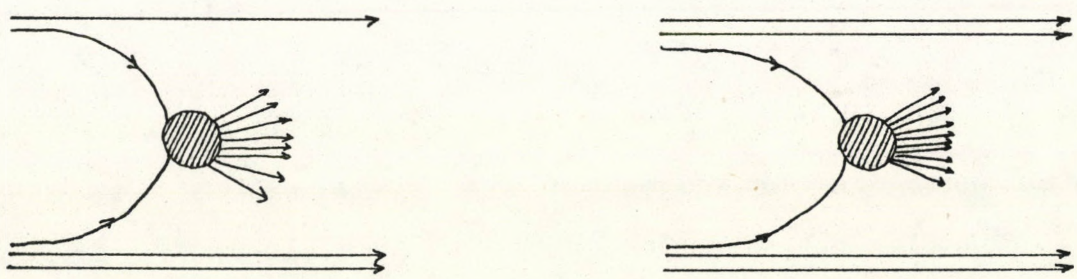
General description of the approach. The spectator mechanism

Considering a picture with quark confinement, one assumes the existence of two equivalent descriptions of the physical processes, namely: the description in terms of quark states and that in terms of real particles, since each quark state corresponds to a set of hadron states.

Our aim is, in a sense, to translate the quark language into the hadron language. Dealing with soft processes (i.e.

processes with small momentum transfer) and especially with inelastic scatterings at high energies, which lead to the production of many particles, we expect to have a large field for comparison with experiment.

The quark combinatorial calculus which has been proposed in[24,25] provides a good possibility to handle the multi-particle production processes. Apart the usual hypothesis about the quark structure of hadrons, two main assumptions have been made. The first one concerned the spectator mechanism, which was based on the picture of spatially separated quarks. As we told already before, practically only one constituent quark of the incident hadron (and of the target) is taking part in the collision process, the other ones remain spectators. As a result of the collision many new quarks are produced, which afterwards join the quarks-spectators and form fast secondary hadrons, observable in experiment. Fig. 4 shows a picture of meson-baryon and baryon-baryon collisions of this kind.



a.)　　b.)

Fig. 4.

If the hadron consists of discrete "dressed" quarks, then inside a fast baryon each of them has to carry about $1/3$ of the total baryon momentum, while inside a meson - about half of the meson momentum. Consequently, multiparticle production processes in hadron-hadron collisions can be divided into two energetically different regions: the central and the fragmentation ones (I and II in Fig. 5).

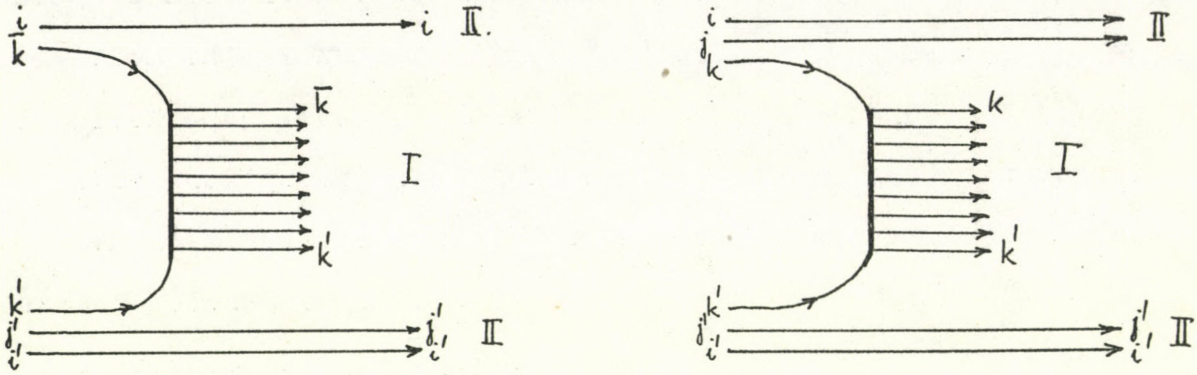


Fig. 5.

The quarks in the central region are sea-quarks, carrying a small fraction of the incident momentum. Joining each other, they form the spectrum of slow hadrons.

The quarks-spectators of the colliding particles (q_i, q_j and $q_{i'}$, $q_{j'}$ in Fig. 5) join quarks (or antiquarks) of the sea forming the hadrons in the fragmentation region. The pair of quarks q_k and $q_{k'}$ produced in the central region after the interaction "remember" their origin and have to be regarded as belonging to the fragmentation region.

Consider now what processes are possible in the fragmentation region. (For the sake of simplicity we consider a baryon fragmentation process). The interacting quark q_k can join the spectators, forming a baryon state containing the same quarks as the incident one (Fig. 6a). If the collision of q_i, q_j and q_k is coherent, then the produced hadron B_{ijk} is analogous to the initial state (in the case of an incident proton that means $p \to p$ transition). If the collision is not coherent, then the produced B^*_{ijk} state is some superposition of possible real hadrons (e.g. $p \to p$, $p \to \Delta^+$ etc).

The spectators q_i, q_j can join a sea quark, in this case a baryon state B_{ij} is formed (Fig. 6b). At the same time q_k together with a sea antiquark form a meson state M_k.

The baryon states B_{ijk} and B_{ij} carry about 2/3 of the momentum of the initial hadron. The interacting quark q_k carries away $x \sim 1/3$ (where $x = \frac{p_L}{p_{max}}$; p_L is the longitudinal momentum of the constituent quark, p_{max} that of the incident hadron. The longitudinal momentum of the newly produced quark q_k which comes from the central region after the interaction, can be estimated assuming that quarks produced in the central region distribute homogeneosly in logx, i.e. their longitudinal momenta follow the geometrical progression law. This is the so-called comb regime which leads to a Regge-pole exchange in elastic scattering. If so, the fastest produced quark has a momentum equal to one half of the incoming quark momentum, the next one 1/4 of it etc. That means, that the meson state M_k is produced in the $x \lesssim 0{,}15$ region.

If one spectator joins two sea quarks, a baryon state $B_i\ (x \sim \frac{1}{3})$ is formed; the other spectator joining a sea antiquark forms a meson state $M_j\ (x \sim \frac{1}{3})$. (Fig. 6c). There are also cases when only meson states are produced (Fig. 6 d,e).

The meson fragmentation process can be considered in the same way. (Fig. 6 f,g,h).

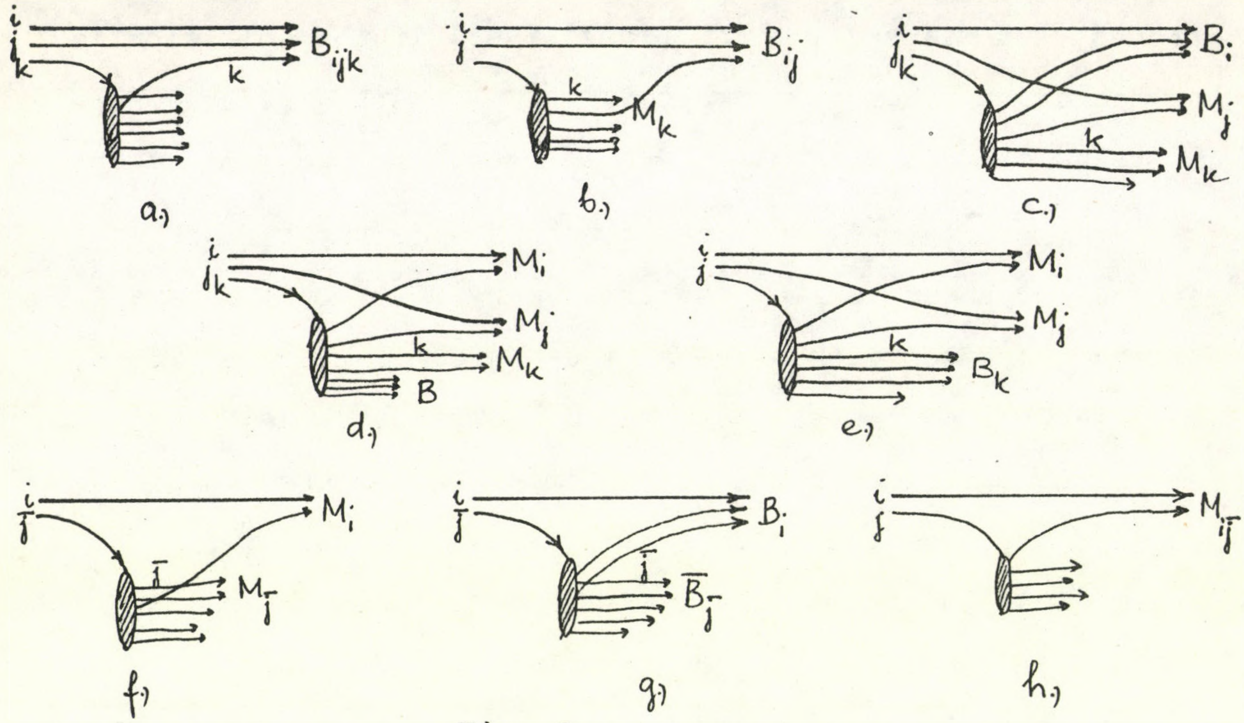


Fig. 6.

As it is seen, the spectator mechanism leads to the production of hadrons with a very definite momentum distribution. The comparison of the theoretical predictions with the experimental data shows a good agreement in different fields, such as resonance production in the region of secondaries with large momenta/26/ as inclusive spectra of seconderies in pp and pA collisions/13-14,27/.

Quark combinatorics. Probabilities of the production of hadron states in the central and fragmentational regions

The second assumption which is made in the quark combinatorial calculus is connected with the newly produced particles. The quark model is SU(6) symmetric. It is natural to assume therefore, that SU(6) symmetry holds for the production processes of secondary particles also. This means that in the multiparticle production processes not only stable particles appear, but resonances also, and the production probabilities of all hadron states belonging to one SU(6) multiplet are equal. Hence, the probability of the hadron production within one SU(6) multiplet is proportional to the number of spin states of these hadrons, i.e. $2J+1$.

In the framework of quark combinatorics it is assumed, that hadrons are formed by quarks with small relative momenta, i.e. by neighbours on the rapidity axis. The quarks join each other with equal probability independently of their quantum numbers and of the fact if they are quarks or antiquarks.

In the central region, where the hadrons are formed by sea quarks only, an arbitrarily chosen particle might be a quark or an antiquark with the same probability : $\frac{1}{2}q + \frac{1}{2}\bar{q}$. The nearest neighbour is again either a quark, or an antiquark. The probability of the states qq, $\bar{q}\bar{q}$ and $q\bar{q}$ is then

$$\left(\tfrac{1}{2}q + \tfrac{1}{2}\bar{q}\right)\left(\tfrac{1}{2}q + \tfrac{1}{2}\bar{q}\right) \to \tfrac{1}{4}qq + \tfrac{1}{4}\bar{q}\bar{q} + \tfrac{1}{2}q\bar{q} \to \tfrac{1}{4}qq + \tfrac{1}{4}\bar{q}\bar{q} + \tfrac{1}{2}M$$

where $M = q\bar{q}$ is a meson state. Taking into account a third possible quark or antiquark, one gets

$$\left(\tfrac{1}{4}qq + \tfrac{1}{4}\bar{q}\bar{q} + \tfrac{1}{2}M\right)\left(\tfrac{1}{2}q + \tfrac{1}{2}\bar{q}\right) \to \tfrac{1}{8}B + \tfrac{1}{8}\bar{B} + \tfrac{3}{4}M\left(\tfrac{1}{2}q + \tfrac{1}{2}\bar{q}\right)$$

where $B = qqq$, $\bar{B} = \bar{q}\bar{q}\bar{q}$. Further iterations lead to the following multiplicity of particles produced in the central region:

$$(q,\bar{q}\text{ - sea}) \to 6N\cdot M + N\cdot B + N\cdot\bar{B} \qquad (3)$$

The number N depends on the total energy of the colliding particles, and increases with the growth of s. Supposing that the multiplicity $N(s)$ is increasing logarithmically, it is convenient to write $N(s) = b \ln \frac{s}{s_0}$ at asymptotic energies. The parameters b and s_0 can not be determined by quark combinatorics, but have to be the same for all processes. Hence, the relation between the produced mesons M, baryons B and antibaryons $\bar{B}$ is[24]:

$$M : B : \bar{B} = 6 : 1 : 1 \tag{4}$$

In the same way one can get relations between baryons and mesons in the fragmentation region too[28]. In this case one considers an incident quark q_i, which, joining a quark or an antiquark of the sea, forms with the probability 2:1 mesons or baryons containing this quark:

$$(q_i + q,\bar{q}\text{-sea}) \rightarrow \frac{1}{3} B_i + \frac{2}{3} M_i + \frac{1}{3} M + N(s) \cdot (6M + B + \bar{B}) \tag{5}$$

Here $B_i = q_i q q$, $M_i = q_i \bar{q}$; $N(s)$ is a large number which is characterized by the number of quarks in the sea.

A similar relation is valid for the case when a pair of quarks $q_i q_j$ transforms into hadrons[28]:

$$(q_i q_j + q,\bar{q}\text{-sea}) \rightarrow \frac{1}{2} B_{ij} + \frac{1}{12}(B_i + B_j) + \frac{5}{12}(M_i + M_j) + \frac{1}{6} M + \\ + N(s) \cdot (6M + B + \bar{B}) \tag{6}$$

The baryon state B_{ij} contains both incident quarks: $B_{ij} = q_i q_j q$.

Supposing, that the quarks q_i, q_j and the quark q_k (Fig. 5) form hadrons in an independent way, the relations (5) and (6) provide a possibility to find the relative weight of the fragmentation processes on Fig. 6b, 6c and 6e: $\frac{1}{2} : \frac{1}{12} : \frac{1}{3}$. The probability of the process 6a can not be obtained in the framework of quark combinatorics.

Hence, if a quark q_k belonging to the baryon B_{ijk} hits the target, fast particles are produced with the following probabilities[29]:

$$B_{ijk} \to \Delta \cdot B_{ijk} + \Delta^* \cdot B^*_{ijk} + (1-\Delta-\Delta^*) \cdot \Big[\tfrac{1}{2} B_{ij} +$$

$$+ \tfrac{1}{12}(B_i + B_j) + \tfrac{5}{12}(M_i + M_j) + \tfrac{1}{3} B_k + \tfrac{2}{3} M_k + \tfrac{1}{2} M\Big] + \cdots \quad (7)$$

Here Δ and Δ^* are the probabilities of the coherent and incoherent transitions $B_{ijk} \to B_{ijk}$ and $B_{ijk} \to B^*_{ijk}$ respectively; they have to be determined from the experiment. In (7) the contribution of hadrons produced in the central region is not written down.

Analogously, the probability of production of fast hadrons after the collision of a meson $M_{i\bar{j}}$ with the target is

$$M_{i\bar{j}} \to \delta \cdot M_{i\bar{j}} + \delta^* \cdot M^*_{i\bar{j}} + (1-\delta-\delta^*) \cdot \Big[\tfrac{1}{3}(B_i + \bar{B}_{\bar{j}}) +$$

$$+ \tfrac{2}{3}(M_i + M_{\bar{j}}) + \tfrac{2}{3} M\Big] + \cdots \quad (8)$$

Here the probabilities δ and δ^* of the processes $M_{i\bar{j}} \to M_{i\bar{j}}$ and $M_{i\bar{j}} \to M^*_{i\bar{j}}$ cannot be defined in the framework of quark combinatorics. It can be shown, that in the quark model the probabilities Δ, Δ^* and δ, δ^* can depend on the initial hadron and on the type of the collision, thus is fact one has to write $\Delta_p(pp)$, $\Delta_p(Kp)$, $\delta_K(Kp)$ and so on. For the sake of simplicity, we will not take this into account.

It is known from the experiment, that the production of strange hadrons is relatively suppressed. According to that, in[24] it was proposed to consider a non-symmetrical quark sea with a relatively suppressed production of strange quarks. This suppression was characterized by a parameter $\lambda \leqslant 1$; in the case of $\lambda = 1$ the symmetry between the quarks u, d, s is restored. The values of λ might be different in the central and the fragmentational region, respectively[30]. This difference can be explained by the fact, that the distributions of the produced strange and non-strange quarks can change with the increase in x in a different way. In the following λ will stand for the parameter of suppression in the central region, whereas in the fragmentation region we shall use λ_f. Moreover, it seems to be sensible to assume, that λ_f obtains different values in different x regions.

To be in a position to compare (7) and (8) with the experimental data, one has to solve another very important problem: what real hadrons correspond to the mesonic and baryonic states B_{ij}, B_i, M_i etc. Indeed, quark combinatorics, while operating with constituent quark states $q\bar{q}$ and qqq does not answer the question by what real particles they are saturated. In[24] the dominance of the lowest SU(6) multiplets was supposed, i.e. the meson 36-plet ($J^P = 0^{-1}, 1^{-1}$) for the $q\bar{q}$ states and the baryon 56-plet ($J^P = \frac{1}{2}^+, \frac{3}{2}^+$) for qqq, respectively. This is a rather rough approach, and, of course, a contribution of hadrons belonging to higher multiplets is quite natural.

The determination of hadrons which are saturating the meson and baryon states is in fact an experimental question, which, in a sense, characterizes the quark confinement. The analysis of experimental data shows, that the contribution of hadrons with $L = 1$ is quite significant: 20-30% of the produced particles. The share of $L = 2$ multiplets seems to be about 10% (Fig. 7).

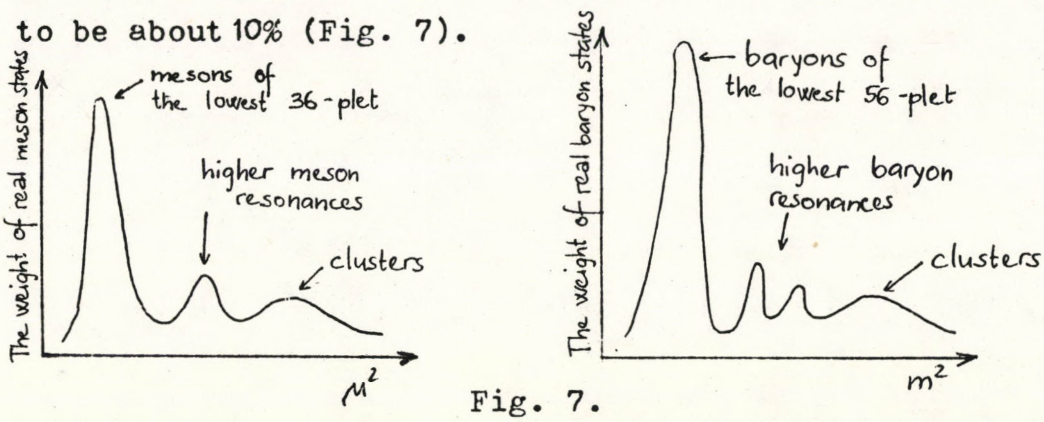


Fig. 7.

In the following we will express the states B_{ij}, B_i, M_i, B, M in the terms of real particles. For the meson states we consider the possibility of multiplets with L=0 and L=1. What concerns the baryons, the experimental evidence on baryon resonance production in multiparticle production processes is rather poor, therefore we restrict ourselves to the lowest L=0 multiplet.

The meson states M_i and M can be written as

$$M_i = \alpha_i(1)M_i(1) + \alpha_i(0)M_i(0)$$
$$M = \alpha(1)M(1) + \alpha(0)M(0) \tag{9}$$

The indices L=0,1 correspond to the s and p - wave states, respectively. The probabilities $\alpha_i(L)$ and $\alpha(L)$ are fixed by the conditions $\alpha_i(1) + \alpha_i(0) = 1$, $\alpha(1) + \alpha(0) = 1$.

Denoting the real mesons belonging to the L=0 multiplet as $h_{M(0)}$ and those with L=1 as $h_{M(1)}$ we can write the decomposition of $M_i(L)$ and $M(L)$ into the real meson states in the form

$$M_i(L) = \sum_h \mu_h^L(i)\, h_{M(L)}$$
$$M(L) = \sum_h \mu_h^L\, h_{M(L)} \tag{10}$$

The coefficients $\mu_h^L(i)$ and μ_h^L (which are the probabilities of observing the meson $h_{M(L)}$ in the states $M_i(L)$ and $M(L)$ respectively) are given in Table 1. The decay modes and their relative probabilities are taken from/31/.

The real hadron content of the states B, B_i and B_{ij} is defined by the coefficients β_h, $\beta_h(i)$ and $\beta_h(ij)$ which are presented in Table 2:

$$B = \sum_h \beta_h h_B$$
$$B_i = \sum_h \beta_h(i) h_B.$$
$$B_{ij} = \sum_h \beta_h(ij) h_B \tag{11}$$

Multiplicities of the secondary particles in the fragmentation region and in the central region

In this paragraph expressions are given for the multiplicities of secondary particles in both the fragmentation and central regions[29]. We consider the cases of incident proton, Λ and Σ^+ hyperons, π^+ and K^+ mesons. Expressions for other incident particles which are of interest can be easily obtained from these ones. For example, the case of a neutron can be obtained from that of a proton by isotopic reflection, i.e. substituting $p \rightleftarrows n$, $\Delta^{++} \rightleftarrows \Delta^-$, $\pi^+ \rightleftarrows \pi^-$, $K^+ \rightleftarrows K^0$. In the case of an initial antiproton one has to confirm charge conjugation, i.e. substitute $p \rightleftarrows \bar{p}$, $\Delta^{++} \rightleftarrows \bar{\Delta}^{--}$ etc.

The relations (7) and (8) and the expressions of B_{ij}, M_i, B_i in terms of the real hadrons enable one to get easily the fragmentation multiplicities. For this purpose one has to take the wave function of the incident particle and to consider all the possible interactions of its constituent quarks.

As an example we consider in detail the fragmentation of the proton. We assume that the incident proton is completely polarized (this fact will be of no significance from the point of view of the result.) The proton wave function in this case is

$$\psi(p^\uparrow) = \sqrt{\tfrac{2}{3}}\{u^\uparrow u^\uparrow d^\downarrow\} - \sqrt{\tfrac{1}{3}}\{u^\uparrow u^\downarrow d^\uparrow\}$$

It is implied that the functions are symmetrized with respect to the SU(6) indices, e.g. $\{u^\uparrow u^\uparrow d^\downarrow\} = \sqrt{\tfrac{1}{3}}(u^\uparrow u^\uparrow d^\downarrow + u^\uparrow d^\downarrow u^\uparrow + d^\downarrow u^\uparrow u^\uparrow)$.

It can be seen immediately, that for the quarks-spectators the probability of being in a $\{u^\uparrow u^\uparrow\}$ state is $2/9$ (interacting is the quark $d^\downarrow$), in $\{u^\uparrow u^\downarrow\}$ - $1/9$, in $\{u^\uparrow d^\uparrow\}$ also $1/9$ respectively. While the quark $u^\uparrow$ is interacting, the spectators are in a state which is described as $\frac{1}{\sqrt{5}}\left(2\{u^\uparrow d^\downarrow\}-\{u^\downarrow d^\uparrow\}\right) \equiv (ud)_p$.

Thus, we have

$$B_{ij} = \frac{2}{9}B(u^\uparrow u^\uparrow) + \frac{1}{9}B(u^\uparrow u^\downarrow) + \frac{1}{9}B(u^\uparrow d^\uparrow) + \frac{5}{9}B_p(ud) .$$

The decompositions of $B(u^\uparrow u^\uparrow)$ and $B(u^\uparrow u^\downarrow)$ into the real hadrons of the 56-plet lead to equal results, and therefore we write

$$\frac{1}{9}B(u^\uparrow u^\downarrow) + \frac{2}{3}B(u^\uparrow u^\uparrow) = \frac{1}{3}B(uu).$$

For the sake of simplicity we introduce the notation $B(u^\uparrow d^\uparrow) = B_1(ud)$. In the case of an incident proton the states B_i and M_i are equal to

$$B_i = \frac{2}{3}B(u) + \frac{1}{3}B(d) \quad \text{and} \quad M_i = \frac{2}{3}M(u) + \frac{1}{3}M(d)$$

respectively. As a result we can write

$$p \to \Delta_p \cdot p + \Delta_p^* \cdot B_p^* + (1-\Delta_p-\Delta_p^*)\Big\{ \frac{1}{2}\Big[\frac{5}{9}B_p(ud) + \frac{1}{3}B(uu) + \frac{1}{9}B_1(ud)\Big] +$$

$$+ \frac{1}{2}\Big[\frac{2}{3}B(u) + \frac{1}{3}B(d)\Big] + \frac{3}{2}\Big[\frac{2}{3}M(u) + \frac{1}{3}M(d)\Big] \tag{12}$$

Expanding the right-hand side in terms of the hadron states h (i.e. the meson states $h_{M(L)}$ and the baryon states

h_B) we, finally, obtain

$$p \to \Delta_p \cdot p + \sum_h h_B \Big\{ \Delta_p^* \beta_h(p) + (1-\Delta_p-\Delta_p^*)\Big[\tfrac{5}{18}\beta_h(ud_p) + \\ + \tfrac{1}{6}\beta_h(uu) + \tfrac{1}{18}\beta_h(ud_1) + \tfrac{1}{3}\beta_h(u) + \tfrac{1}{6}\beta_h(d)\Big]\Big\} + \\ + (1-\Delta_p-\Delta_p^*)\cdot \sum_{L=0,1}\sum_h h_{M(L)}\,\alpha_i(L)\Big[\mu_h^L(u) + \tfrac{1}{2}\mu_h^L(d)\Big] \tag{13}$$

Introducing for the multiplicity of the secondary hadron in the fragmentation region of proton the notation $F_h(p)$ we can re-write (10) in the form

$$p \to \sum_h F_h(p)\cdot h \tag{14}$$

Similarly to the incident proton case, the multiplicities of Λ and Σ^+ hyperons in the fragmentation region can be calculated:

$$\Lambda \to \sum_h F_h(\Lambda)\cdot h = \Delta_\Lambda \cdot \Lambda + \sum_h h_B \Big\{ \Delta_\Lambda^* \beta_h(\Lambda) + \\ + (1-\Delta_\Lambda-\Delta_\Lambda^*)\Big[\frac{\zeta}{2(2+\zeta)}\beta_h(ud_\Lambda) + \frac{1}{4(2+\zeta)}\big(\beta_h(us_1)+\beta_h(ds_1)+\beta_h(us_0)+\beta_h(sd_0)\big) + \\ + \frac{2\zeta+1}{6(2+\zeta)}\beta_h(s) + \frac{5+\zeta}{12(2+\zeta)}\big(\beta_h(u)+\beta_h(d)\big)\Big]\Big\} + \\ + (1-\Delta_\Lambda-\Delta_\Lambda^*)\sum_{L=0,1}\sum_h h_{M(L)}\,\alpha_i(L)\Big[\frac{5+4\zeta}{6(2+\zeta)}\mu_h^L(s) + \\ + \frac{5\zeta+13}{12(2+\zeta)}\big(\mu_h^L(u)+\mu_h^L(d)\big)\Big] \tag{15}$$

$$\Sigma^+ \to \sum_h F_h(\Sigma^+)\cdot h = \Delta_\Sigma \cdot \Sigma^+ + \sum_h h_B \Big\{ \Delta^*_\Sigma \beta_h(\Sigma^+) +$$
$$+ (1-\Delta_\Sigma - \Delta^*_\Sigma)\Big[\frac{\zeta}{2(2+\zeta)}\beta_h(uu) + \frac{5}{6(2+\zeta)}\beta_h(us_\Sigma) + \frac{1}{6(2+\zeta)}\beta_h(us_1) +$$
$$+ \frac{\zeta+5}{6(2+\zeta)}\beta_h(u) + \frac{1+2\zeta}{6(2+\zeta)}\beta_h(s)\Big]\Big\} +$$
$$+ (1-\Delta_\Sigma - \Delta^*_\Sigma)\cdot \sum_{L=0,1}\sum_h h_{M(L)}\cdot \alpha_i(L)\Big[\frac{5\zeta+13}{6(2+\zeta)}\mu^L_h(u) +$$
$$+ \frac{5+4\zeta}{6(2+\zeta)}\mu^L_h(s)\Big] \qquad (16)$$

Differantly from the proton case, in (15) and (16) it is taken into account, that the cross section of the interaction is less for the strange quark than for the non-strange one. Their ratio $\zeta = \sigma_{inel}(sq)/\sigma_{inel}(qq)$ is near to 2/3.

Formula (8) enables us to calculate the fragmentation secondaries for incident mesons. In the cases of π^+ and K^+ we obtain the following

$$\pi^+ \to \sum_h F_h(\pi^+)\cdot h = \delta_\pi \cdot \pi^+ + \sum_{L=0,1}\sum_h h_{M(L)}\cdot \alpha_i(L)\cdot\Big\{\delta^*_\pi \mu^L_h(\pi^+) +$$
$$+ (1-\delta_\pi - \delta^*_\pi)\Big[\frac{2}{3}\mu^L_h(u) + \frac{2}{3}\mu^L_h(\bar d)\Big]\Big\} +$$
$$+ \sum_h h_B(1-\delta_\pi - \delta_{\pi^*})\cdot\frac{1}{3}\beta_h(u) + \sum_h h_{\bar B}(1-\delta_\pi - \delta_{\pi^*})\cdot\frac{1}{3}\beta_h(\bar d) \qquad (17)$$

$$K^+ \to \sum_h F_h(K^+)\cdot h = \delta_K \cdot K^+ + \sum_{L=0,1}\sum_h h_{M(L)}\cdot \alpha_i(L)\cdot\Big\{\delta^*_K \mu^L_h(K^+) +$$
$$+ (1-\delta_K - \delta^*_K)\cdot\Big[\frac{2}{3}\mu^L_h(u) + \frac{2}{3}\mu^L_h(\bar s)\Big]\Big\} +$$
$$+ \sum_h h_B(1-\delta_K - \delta^*_K)\cdot\frac{1}{3}\beta_h(u) + \sum_h h_{\bar B}(1-\delta_K - \delta^*_K)\frac{1}{3}\beta_h(\bar s) \qquad (18)$$

In (18) the parameter ζ does not occur, because, due to (7), the secondary hadron content is equal for the quark-spectator and for the quark which underwent the interaction.

In the central region the multiplicity of secondary particles is given by (3). Due to the additive quark model, the energy which is used for the production of new (sea) quarks is determined by the energy of colliding quarks. In the pion-nucleon collision the square of this energy is about $1/6$, in nucleon-nucleon collision about $1/9$ of the total energy of hadrons. That means, that in the case of pion-nucleon collision we have

$$N_{\pi N}(s) = b \ln \frac{s}{6s_0} = b \ln \frac{s}{s^0_{\pi N}} \tag{19}$$

while for the nucleon-nucleon case

$$N_{NN}(s) = b \ln \frac{s}{9s_0} = b \ln \frac{s}{s^0_{NN}} \quad . \tag{20}$$

In the collision processes of strange particles one has to remember the difference between the cross-sections of the interaction of strange and non-strange quarks, and the fact that the heavier strange quark takes away a larger part of the hadron momentum. Hence, for the kaon-nucleon collision one obtains

$$N_{KN}(s) = \frac{b\zeta}{1+\zeta} \ln \frac{s}{3(1+\mu)s_0} + \frac{b}{1+\zeta} \ln \frac{s\mu}{3(1+\mu)s_0} = b \ln \frac{s}{s^0_{KN}} \tag{21}$$

where $\mu = \frac{m_q}{m_s} \approx \frac{2}{3}$ is the ratio of the strange and non-strange quarks. Finally,

$$N_{\Lambda N}(s) = N_{\Sigma N}(s) = \frac{2b}{2+\zeta} \ln \frac{s\mu}{3(1+2\mu)s_0} + \frac{\zeta b}{2+\zeta} \ln \frac{s}{3(1+2\mu)s_0} = b \ln \frac{s}{s^0_{\Lambda N}} \qquad (22)$$

The obtained expressions give a possibility to calculate the absolute values of average multiplicities of secondary particles in hadron-hadron collisions. The parameters are fitted to the experimental data and according to them the coefficients in (19)-(22) are calculated[29]. (For example, the value of λ is selected to give the best agreement with the experimental K/π ratio in the central region and is found to be 0,3). Supposing that the probabilities Δ and δ of the coherent processes $B_{ijk} \to B_{ijk}$ and $M_{i\bar{j}} \to M_{i\bar{j}}$ are mostly of diffractional origin, the value of these probabilities is estimated using the data on diffraction scattering. In the additive quark model the cross sections of diffraction processes in the meson-nucleon and baryon-nucleon scatterings are determined by the diagrams in Fig. 8.

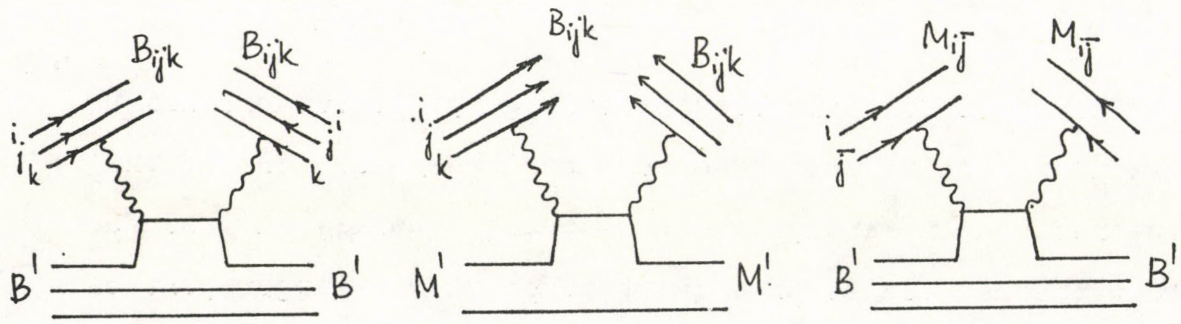
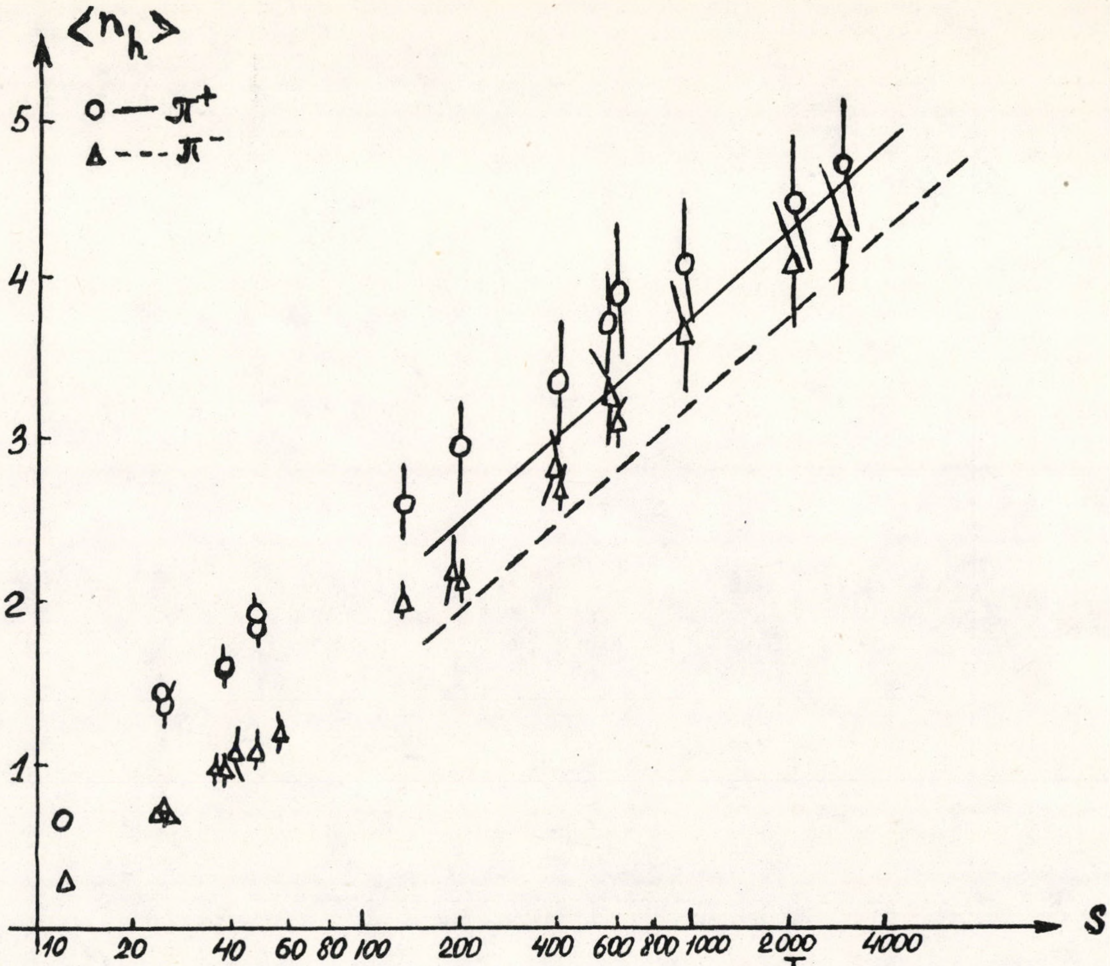


Fig. 8.

(For the values of Δ and δ see[29]).

The experimental data on average multiplicities of secondary hadrons in the pp, πp and Kp collisions permit us to prove the basic statements of quark combinatorics.

a./



b./

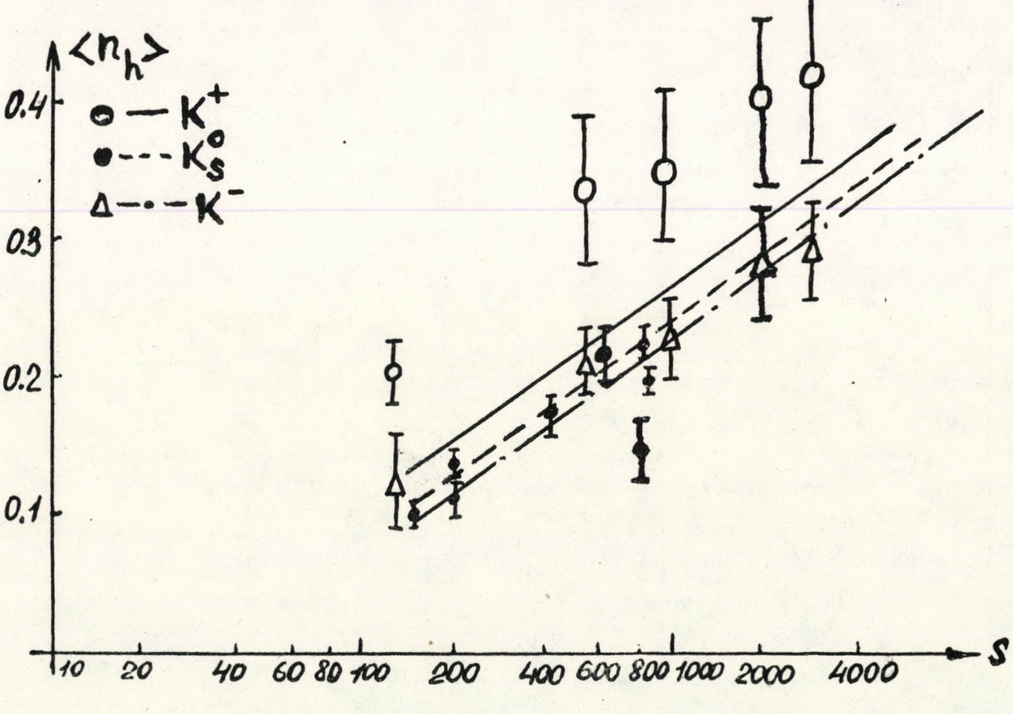
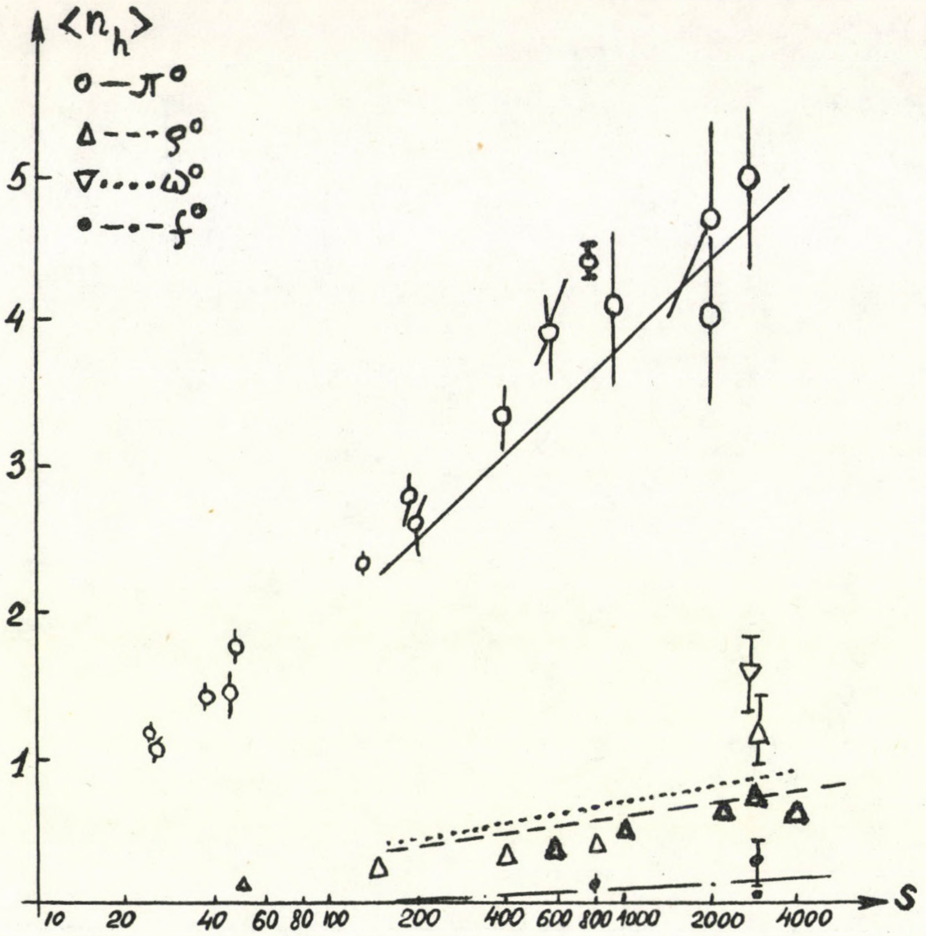


Fig. 9. Average multiplicities of secondary particles in pp collisions. The straight lines correspond to the predictions of the model see /29/

Fig. 9. a./ b./

c./



d./

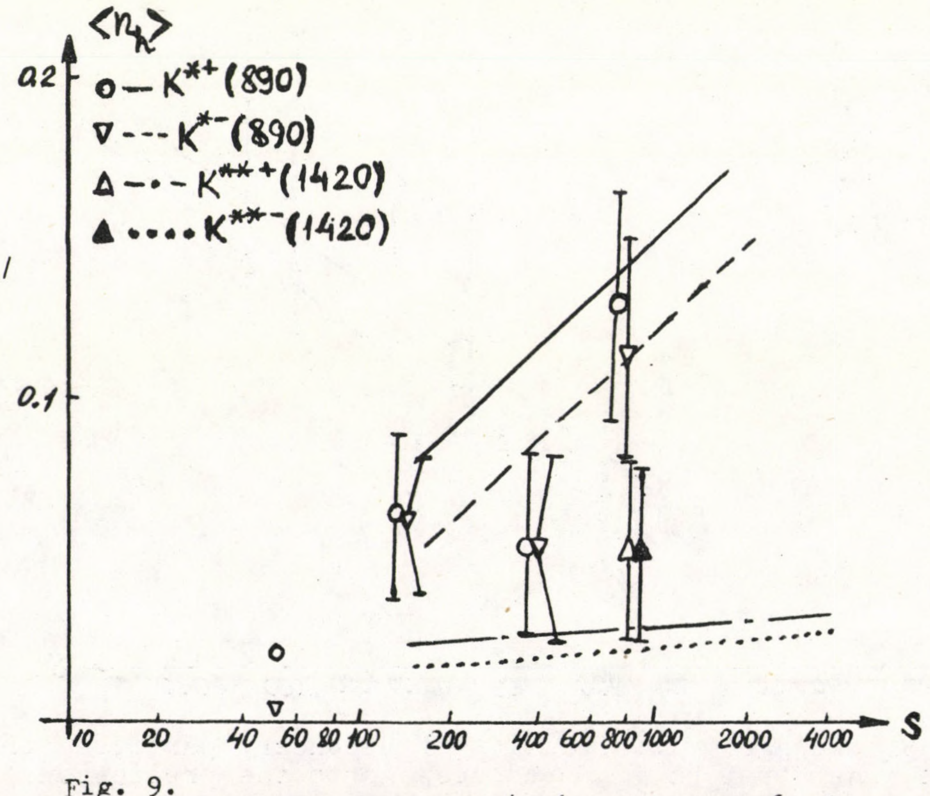


Fig. 9.

pp p_{lab}=69 GeV/c / /; 12,4 GeV/c 6 /; 19 GeV/c / /
69 GeV/c / /; 1oo GeV/c
pp 24 GeV/c /; 69 GeV/c 2o5 GeV/c etc.

Fig. 9. c./ d./

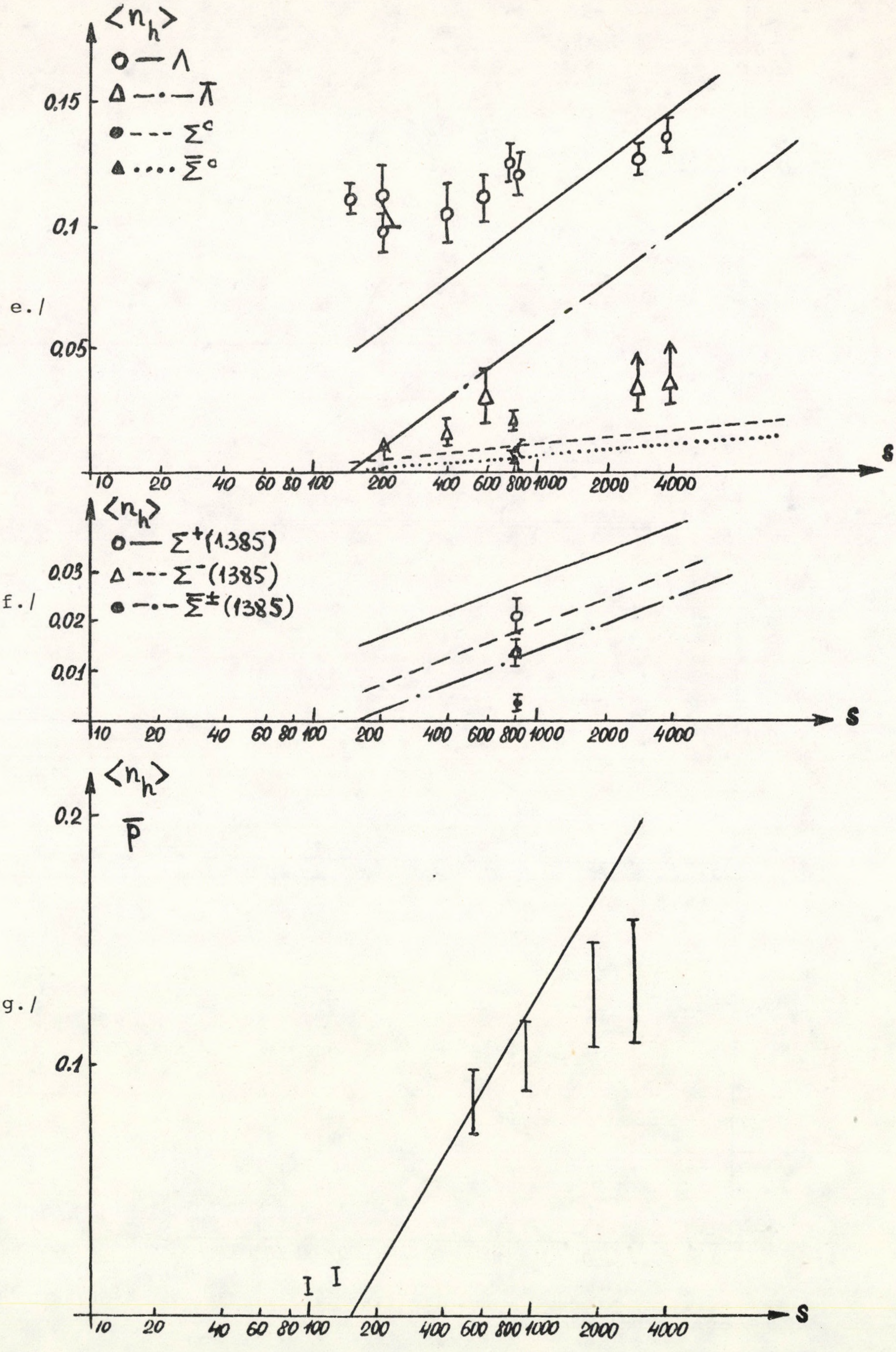

e./
⟨n_h⟩
○ — Λ
Δ —·— Λ̄
● - - - Σ°
▲ ···· Σ̄°
0.15
0.1
0.05
s
10 20 40 60 80 100 200 400 600 800 1000 2000 4000
f./
⟨n_h⟩
○ — Σ⁺(1385)
Δ - - - Σ⁻(1385)
● -·- Σ̄±(1385)
0.03
0.02
0.01
s
10 20 40 60 80 100 200 400 600 800 1000 2000 4000
g./
⟨n_h⟩
p̄
0.2
0.1
s
10 20 40 60 80 100 200 400 600 800 1000 2000 4000

Fig. 9. e,f,g

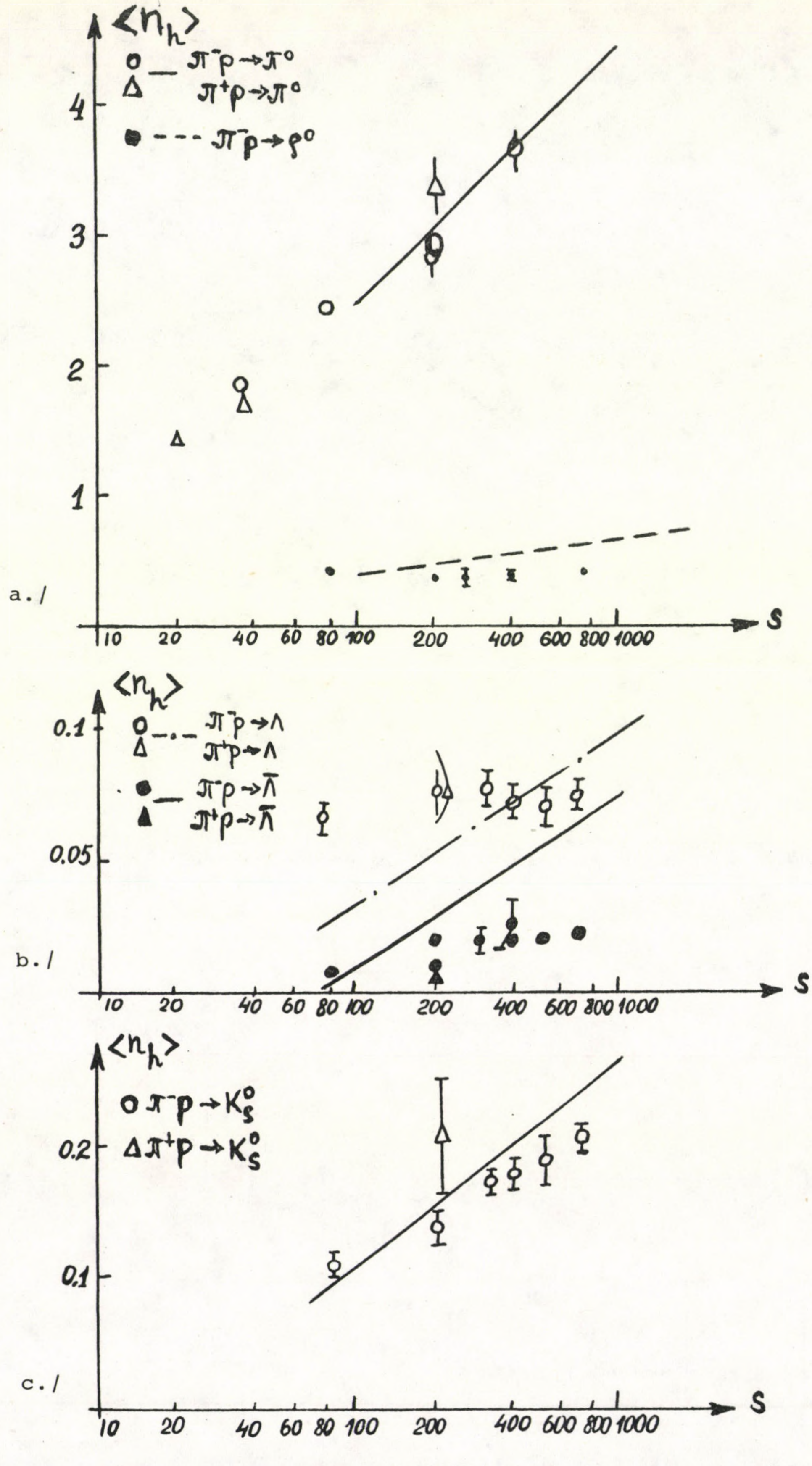


Fig. 1o. Average multiplicities of secondary particles in $\pi^{\pm}p$ collisions.

Fig. 10 a,b,c

Consider first the meson production processes. In Figs. 9-11 the data on average multiplicities of secondary mesons in pp (fig. 9), $\pi^{\pm}p$ (fig.10) and $K^{-}p$ (fig. 11) collisions at high energies are presented. The straight lines correspond to the predictions of the quark combinatorial calculus. In each case there is a satisfactory agreement of the theory and the experiment.

What concerns the baryons and the baryon resonances, the experimental data and the corresponding predictions of the quark model agree only roughly. For example, the ratios Λ/Σ^{0}, $\Sigma^{+}(1385)/\Sigma^{0}$ and $\Sigma^{-}(1385)/\Sigma^{0}$ satisfy the prediction quite well, what corresponds to the idea of baryons produced in SU(6) multiplets. The same ratios indicate that there might be a significant contribution of higher resonances. (For details see[29]).

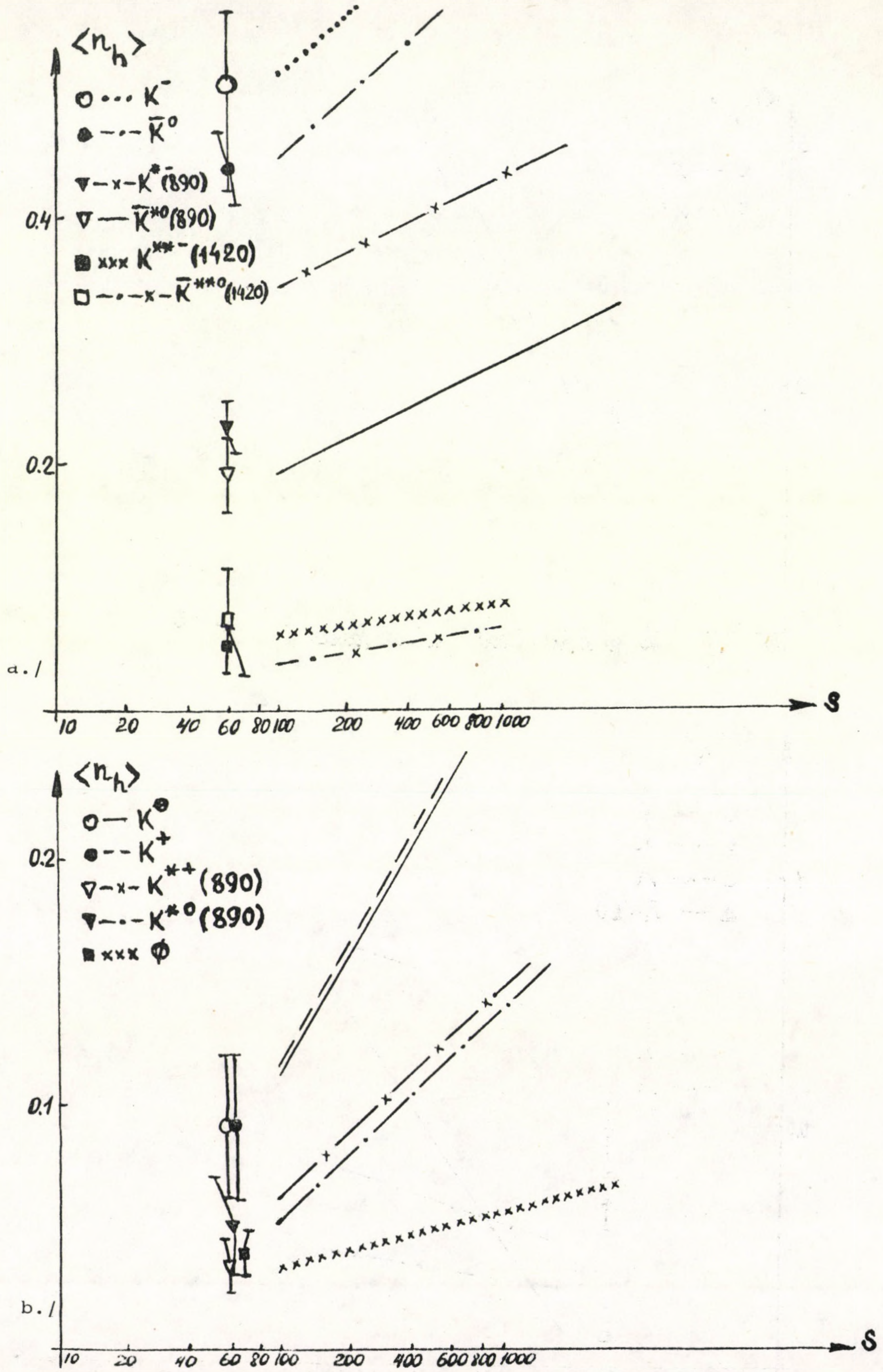
As an example for a quite good agreement of the predictions of quark combinatorics with the experimental data let us consider the ratio of secondaries with total quark spins 0 and 1. In the framework of quark combinatorial calculus one assumes, that in the multiparticle production process a cloud of quarks and antiquarks with non-correlated spin projections is formed. In such a cloud the ratio of the number of pairs $q\bar{q}$ with total quark spin $s_{q\bar{q}} = 1$ and of those with $s_{q\bar{q}} = 0$ is 3:1. Supposing that the mesons are formed by quarks and antiquarks independently of their spin projections, this ratio has to be true for the produced mesons too: the multiplicity of meson states with $s_{q\bar{q}} = 1$ is proportional to the multiplicity of $s_{q\bar{q}} = 0$ states as 3:1. In hadron-hadron collisions this relation is true for both the fragmentational and the central regions.

The condition 3:1 has to be fulfilled for mesons belonging to the same SU(6) multiplet. Examples for that can be the well known relations $\rho : \pi = K^* : K = 3 : 1$ for the directly produced mesons of the lowest 36-plet. Summarizing over all multiplets, we get

$$\frac{\sum_L \langle n_{M(L;S=1)} \rangle}{\sum_L \langle n_{M(L;S=0)} \rangle} = 3 \tag{23}$$

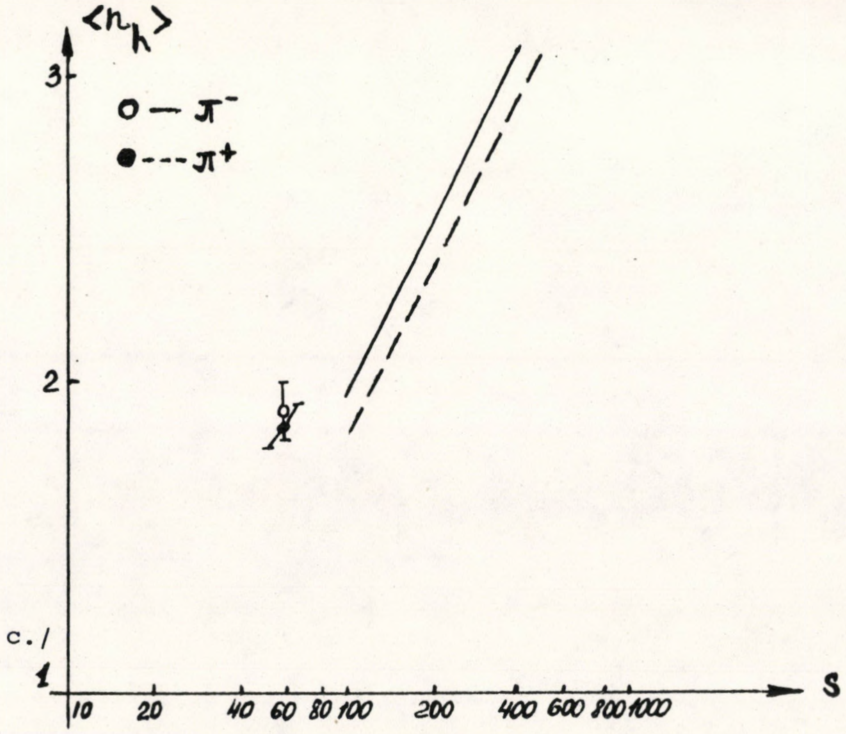
It is convenient to prove this relation on secondary K -mesons $K, K^*(890), K^*(1420)$ because strange particles appear as decay products to a less extent than π -mesons.

The experimental data on $pp \rightarrow$ kaons (405 GeV/c)[32] and $K^- p \rightarrow$ kaons (32 GeV/c)[33] provide a possibility to test the condition (23). The results of the measurements are given in Table 3. The main contribution to the cross-section is given by the production of the $L=0$ multiplet. Indeed, due to the combinatorial calculus the direct production of the vector mesons is three times as large as that of the pseudoscalar mesons. Thus the total amount of secondary mesons with $L=0$ is 4/3 V. The weight of tensor mesons in the $L=1$ multiplet is 5/12, hence 12/5 T mesons with $L=1$ are produced. The production of mesons with $S_{q\bar{q}}=1$ in the multiplets with $L=0$ and $L=1$ is V and $9/5\,T$, respectively. The value $V+\frac{9}{5}T$ which is the contribution of mesons with $S_{q\bar{q}}=1$ in the S -wave and P -wave multiplets, is given in Table 3. As it is seen from the data, the experimental value is in each case near to 75% of

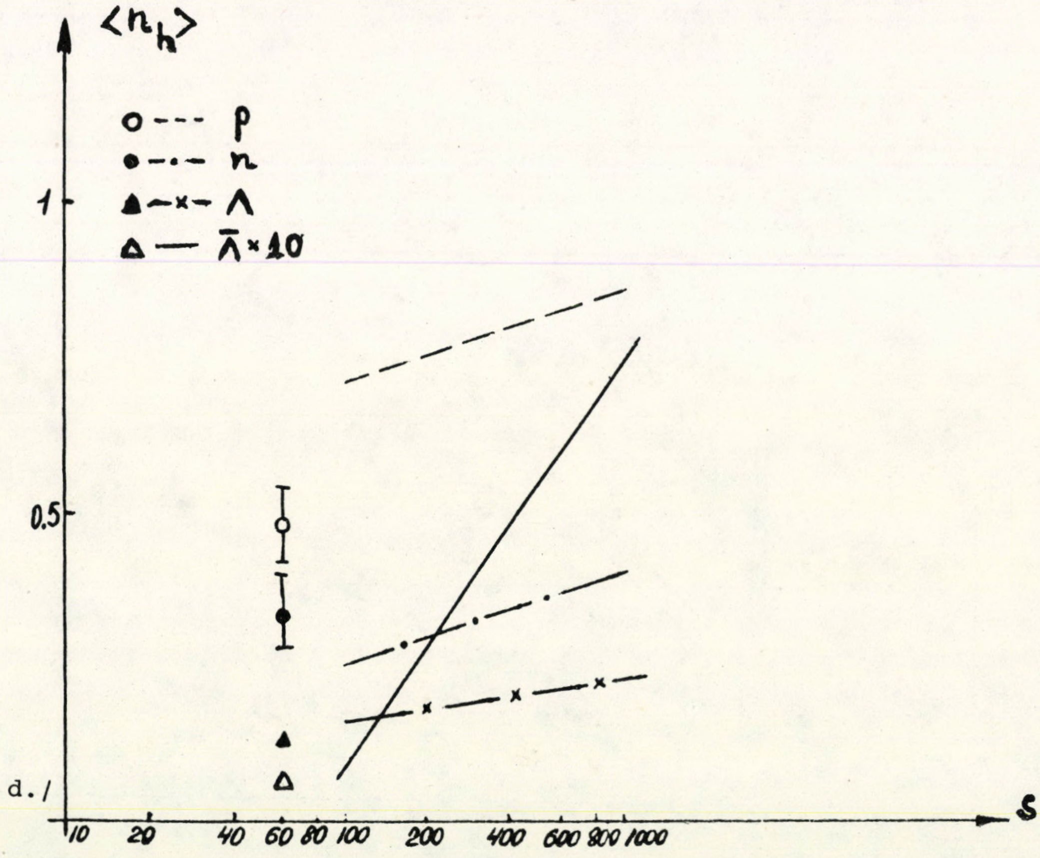


⟨n_h⟩
K⁻
K̄⁰
K*⁻(890)
K̄*⁰(890)
K**⁻(1420)
K̄**⁰(1420)
0.4
0.2
a./
10 20 40 60 80 100 200 400 600 800 1000
S
⟨n_h⟩
K⁰
K⁺
K*⁺(890)
K*⁰(890)
φ
0.2
0.1
b./
10 20 40 60 80 100 200 400 600 800 1000
S

Fig.II. a.,b.,

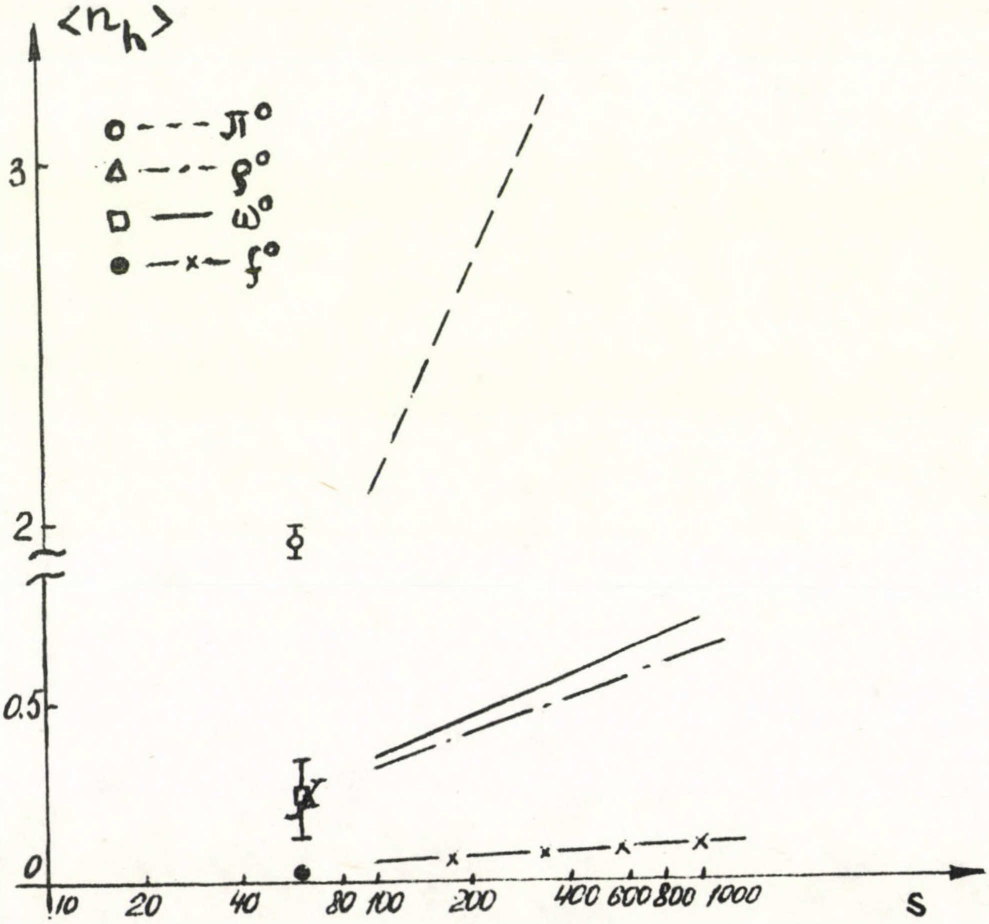


<nh>
3
2
1
o — π⁻
● --- π⁺
c./
10
20
40
60
80
100
200
400
600
800
1000
s



<nh>
1
0.5
o --- p
● -·- n
▲ -x- Λ
Δ — Λ̄×10
d./
10
20
40
60
80
100
200
400
600
800
1000
s

Fig.11. c., d.,



$\langle n_h \rangle$
π^0
ρ^0
ω^0
f^0
3
2
0.5
0
10
20
40
80
100
200
400
600
800
1000
S

Fig. II.e.

the total cross sections of kaons, in accordance with the predictions of quark combinatorics.

Hadron-nucleus interactions

In the previous paragraph it was demonstrated that the investigation of multiparticle production processes provides a good possibility to prove the main assumptions of the presented approach, especially that concerning the extension of SU(6) symmetry. There are, however, processes, which allow to observe in a relatively pure way the consequences of the spectator mechanism, i.e. to prove the hypothesis which is the crucial one from the point of view of the hadron structure. These processes are the hadron-nucleus collisions at high energies. They enable us to test the hadron structure because of the well-known fact that the fast secondary hadrons do not multiply by possible repeated collisions with the nuclear matter. This can be explained by the parton hypothesis: secondaries need time to be formed.[23,34]. For fast particles this time increases with their momentum p : $\tau \sim \frac{p}{m^2}$. That means, that the constituents go through the nucleus before forming a secondary hadron, and, of course, they do not interact repeatedly with the nucleus.

As it was told already, in hadron-hadron collisions only one pair of consituent quarks takes part in the interaction (Fig. 5.). In a collision with a heavy nucleus, however, while going through the nuclear matter, the other constituents of the incident hadron can also interact. In the case of a superheavy nucleus all the constituents of the projectile would interact, so that all the three or two quarks of an incident baryon or meson would break up. As a result, for example the multiplicity ratio of the secondaries in the central region for πA and pA interactions would be $\sim 2/3$ /11/. For real nuclei (even for $A \sim 200$) a part of the constituent quarks still goes through a nucleus without interacting. The quarks which go through the nucleus without interaction determine the number of the fragmentational hadrons i.e. hadrons in the region of large x .

Hence, in baryon-nucleus collisions three different processes are possible: one quark is interacting, two go through the nucleus; two quarks are interacting, one goes through the nucleus; and finally, all three quarks interact. In meson-nucleus interactions one or two quarks of the incident meson can take part in the interaction. (These processes are shown in Fig.12).

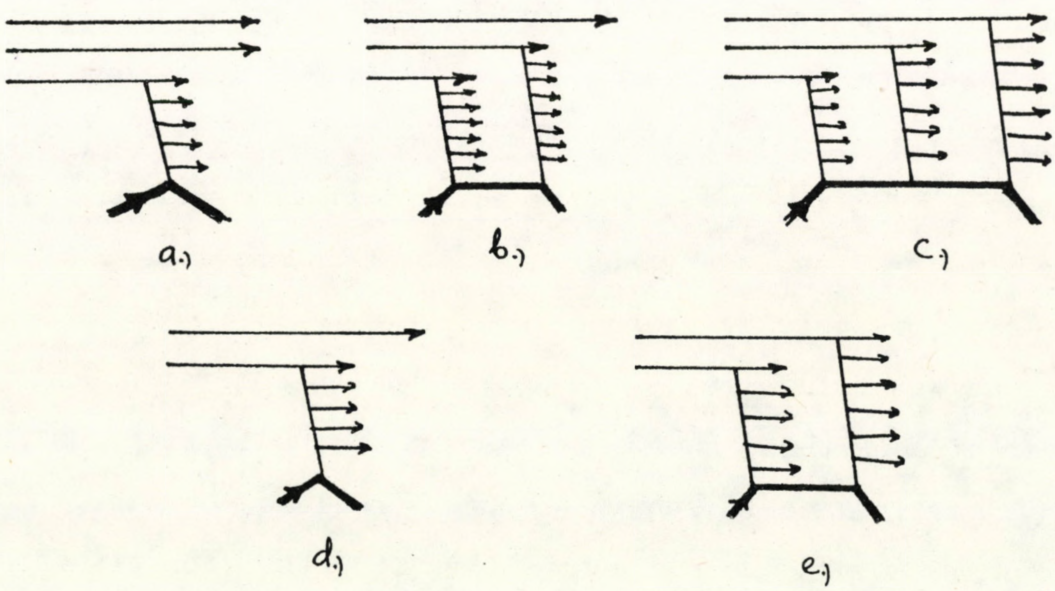


Fig.12.

Accepting the hadron picture with spatially separated quarks we assume that the constituent quarks interact with the nuclear matter in a independent way. The probability for a quark to interact is calculated as a function of the nuclear matter density and the quark-nucleon cross section

$$\sigma_{inel}(qN) \simeq \frac{1}{3}\sigma_{inel}(NN) \simeq \frac{1}{2}\sigma_{inel}(\pi N)$$

The probabilities of the processes ban be written as

$$V_k^h = \frac{n!}{(n-k)!\,k!\,\sigma_{prod}} \int d^2b\, e^{-(n-k)\sigma_{inel}(qN)T(b)} \left[1 - e^{-\sigma_{inel}(qN)T(b)}\right]^k \tag{24}$$

where k is the number of the interacting quarks, and h_n is the incident hadron consisting of n quarks/13/.
The probability

$$\sigma_{prod} = \int d^2b \left[1 - e^{-n\sigma_{inel}(qN)T(b)}\right] \tag{25}$$

has the meaning of the inelastic hadron-nucleus cross-section with the production of at least one secondary hadron and is obtained from the condition $\sum_{k=1}^{n} V_k^h = 1$. The function $T(b)$ is expressed in terms of the nuclear density

$$T(b) = A\int_{-\infty}^{\infty} dz\, \rho(b,z) \tag{26}$$

For $\rho(r = \sqrt{b^2+z^2})$, the Fermi parametrization,

$$\rho(r) = \frac{\rho_0}{1+\exp[(r-c_1)/c_2]}, \quad 4\pi\int_0^{\infty}\rho(r)r^2dr = 1 \tag{27}$$

is accepted. The c_1 and c_2 parameters are taken from the data on eA scattering[35,36].

In the following we present the relative multiplicities of secondary particles in the central region. The multiplicities of secondaries n_{pA} and $n_{\pi A}$ in the pA and πA collisions can be expressed, using the formulae (24), in the form

$$R\left(\frac{pA}{qA}\right) = \frac{n_{pA}}{n_{qA}} = \sum_{k=1}^{3} k V_k^p = \frac{3}{\sigma_{prod}^{pA}} \int d^2b \left(1 - e^{-\sigma_{inel}(qN) T(b)}\right)$$

$$R\left(\frac{\pi A}{qA}\right) = \frac{n_{\pi A}}{n_{qA}} = \sum_{k=1}^{2} k V_k^{\pi} = \frac{2}{\sigma_{prod}^{\pi A}} \int d^2b \left(1 - e^{-\sigma_{inel}(qN) T(b)}\right) \qquad (28)$$

The ratio of the multiplicities in the meson-nucleus and nucleon-nucleus scatterings does not depend on n_{qA} and is equal to

$$R\left(\frac{\pi A}{pA}\right) = \frac{n_{\pi A}(y)}{n_{pA}(y)} = \frac{2\sigma_{prod}^{pA}}{3\sigma_{prod}^{\pi A}} = \frac{V_1^{\pi}(A) + 2V_2^{\pi}(A)}{V_1^p(A) + 2V_2^p(A) + 3V_3^p(A)} \qquad (29)$$

The multiplicities $n_{\pi A}$ and n_{pA} might depend on the value of the rapidity of the corresponding secondaries. The comparison of the right-hand side of (29) with the experimental data is presented in Fig.13.

The calculated value of $R\left(\frac{\pi A}{pA}\right)$ is in agreement with experiment in the interval $1,5 < \eta < 3,5$ for the nuclei C(A=12) and Pb(A=207) and for the fotoemulsion $\frac{1}{2}Ag + \frac{1}{2}Br$. The considered region for the values of the quasirapidity

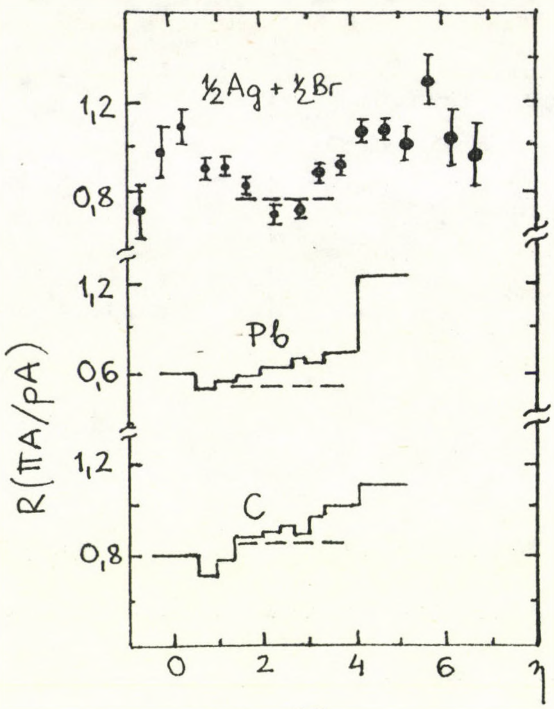


Fig. 13.

$\eta = -\ln tg\, \theta/2$ corresponds just to the central region of the collision processes.

The ratios of the secondaries in πA and πp scatterings and in pA and pp scatterings depend, due to (28), on the ratios n_{qA}/n_{qq} (where n_{qq} is the multiplicity in the quark-quark collision) :

$$R\left(\frac{\pi A}{\pi p}\right) = \left[V_1^{\pi}(A) + 2V_2^{\pi}(A)\right]\frac{n_{qA}(y)}{n_{qN}(y)} \tag{30}$$

$$R\left(\frac{pA}{pp}\right) = \left[V_1^{p}(A) + 2V_2^{p}(A) + 3V_3^{p}(A)\right]\frac{n_{qA}(y)}{n_{qN}(y)} \tag{31}$$

In Fig. 14 the experimental values averaged in the interval $2,5 < \eta < 3,5$ are shown for $R\left(\frac{pA}{pp}\right)$ (▲) and $R\left(\frac{\pi A}{\pi p}\right)$ (▼) as functions of A. In this interval (29) is fulfilled for $R\left(\frac{\pi A}{pA}\right)$, and one can take $n_{qA} \simeq n_{qN}$.

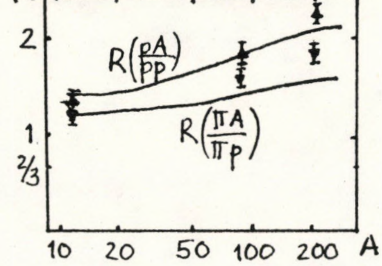
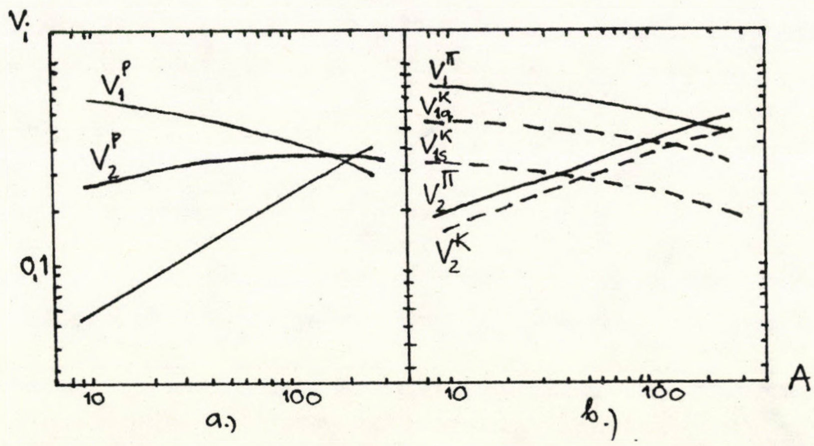


Fig. 14.

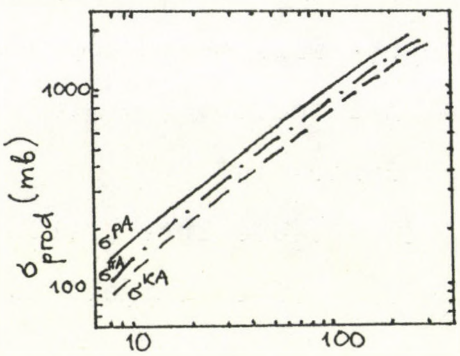
In the following the multiplicities of secondary hadrons in the fragmentation region are calculated as functions of the atomic number A of the target.

The $V_1^p(A)$, $V_2^p(A)$, $V_3^p(A)$ and σ_{prod}^{pA} values are shown in figs. 15 and 16.



The probability of absorbing a different number of incident quarks in hadron-nucleus interactions. The probabilities to absorb one, two or three quarks in a pA collision. (a.) The quark absorption probabilities for pA (solid lines) and KA (dashed lines) interactions.

Fig. 15.



The inelastic hadron-nucleus cross sections with the production of at least one secondary hadron as functions of A.

Fig. 16.

One sees that for light nuclei the most important is the process of fig.12a; however even for Be the probability of the process of fig. 12b, with two interacting quarks, is not small ($\simeq 25\%$). For $A > 30$, the probability of the process of fig.12a with two spectators decreases roughly as $A^{-1/3}$. For $A > 100$, the probabilities of all three processes are of the same order. As for the proton-nucleus cross section σ^{pA}_{prod} in fig.16, it increases as $A^{2/3}$ for $A > 30$, in full accordance with expectations.

As already said, the model with three spatially separated quarks enables one to express the multiplicity of a fast secondary baryon with $x \simeq \frac{2}{3}$ for proton-nucleus collisions, in terms of the similar quantity for pp interactions. Production of that fast baryon proceeds in both cases by picking up a newly made quark of the sea by the two non-interacting spectators. The upper vertices in figs. 5b and 12a are the same, so they cancel in the ratio of the cross sections or multiplicities. Therefore the ratio of the inclusive cross sections for the pA and pp collisions must not depend on x in a region near $x = 2/3$. Such independence of x represents a test of the hypothesis on the spatial separation of the three constituents in a nucleon, whatever the formation mechanism of the secondaries is.

The calculated ratio of the absolute proton yields, with $x \simeq 2/3$, from the nucleon and proton targets is

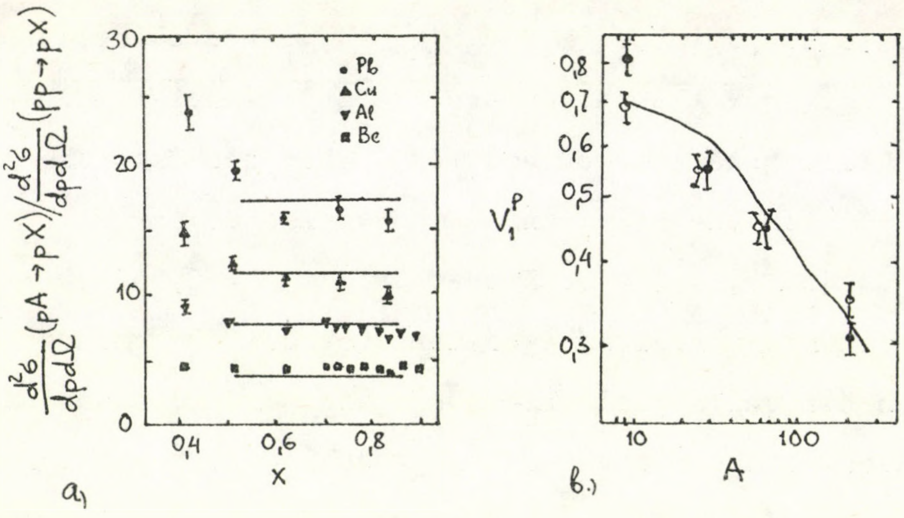
$$\frac{\frac{d^2\sigma}{dp\,d\Omega}(pA \to pX)}{\frac{d^2\sigma}{dp\,d\Omega}(pp \to pX)} = V_1^p(A)\,\frac{\sigma^{pA}_{prod}}{\sigma^{pp}_{inel}} \tag{32}$$

The results of our calculation are displayed in fig. 17a for the Be, Al, Cu and Pb nuclei together with the data obtained at 19.2 GeV/c[37]. Theory and experiment are consistent in the wide range $0,55 \leqslant x \lesssim 0,85$ where the experimental x-dependence of the ratio (32) is essentially flat. This indicates the absence of a substantial spread in momenta (with $\Delta x \gtrsim 1/6$) of the constituents.

The experimental magnitudes of the V_1^p obtained from the data of ref. /37/ by using eq. (32) are shown in fig. 17b to be consistent with our calculation.

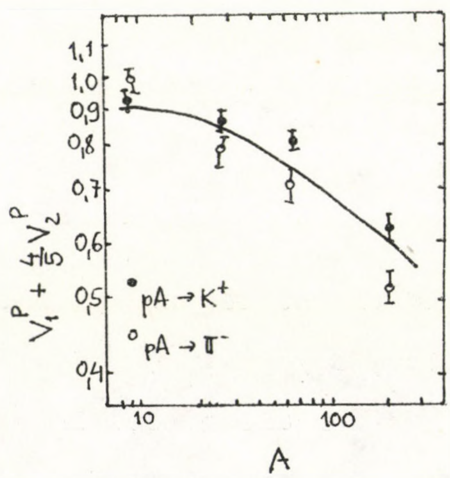
The ratio of the meson yields near $x = \frac{1}{3}$ is obtained using the expressions (5), (6):

$$\frac{\frac{1}{\sigma^{pA}_{prod}}\,\frac{d^2\sigma}{dp\,d\Omega}(pA \to MX)}{\frac{1}{\sigma^{pp}_{inel}}\,\frac{d^2\sigma}{dp\,d\Omega}(pp \to MX)} = V_1^p(A) + \frac{4}{5}\,V_2^p(A) \tag{33}$$



a.) The cross-section ratios for nuclei and for hydrogen for p=19,2GeV/c Θ=12,5 mr as a function of x of the secondary /37/. b.) Multiplicity of the secondary protons, averaged over the interval o,52 $\leq$ x $\leq$ o,85 for p_o=19,2 GeV/c and Θ=12,5 mr (closed circles)/37/, and for p_o = 24 GeV/c and Θ=17 mr (open circles) /46/, as a function of A.

Fig. 17.



Multiplicities of mesons in proton-nucleus interactions at p_o=19,2GeV/c and Θ=12,5 mrad /37/. The closed and open circles correspond to the production of $K^+$and π^-respectively at x=o,34.
Fig. 18.

In fig. 18 we plot the $V_1^p + \frac{4}{5}V_2^p$ values calculated according to eq.(24). Also shown are the experimental magnitudes of the left-hand side of eq. (33), obtained from the data of ref.[37] on the π^- and K^+ yields at p_{lab} = 19.2 GeV/c, θ = 12,5 mrad and x = 0,34 for the Be, Al, Cu and Pb nuclei. Agreement between the theory and experiment is quite good. The π^- and K^+ mesons have been chosen since the chance of producing such particles near $x = \frac{1}{3}$ as resonance decay products is negligible. The opposite case of π^+ production at $x \simeq \frac{1}{3}$ is probably dominated just by the baryonic resonance decays, and therefore is not considered. here.

When a pion strikes a nucleus or a proton, the ratio of inclusive spectra of the same fragments at $x \simeq \frac{1}{2}$ containing one of the pion quarks, must be

$$\frac{\dfrac{1}{\sigma_{prod}^{\pi A}} \dfrac{d^2\sigma}{dp\,d\Omega}(\pi^- A \to h X)}{\dfrac{1}{\sigma_{inel}^{\pi p}} \dfrac{d^2\sigma}{dp\,d\Omega}(\pi^- p \to h X)} \qquad h = \pi^-, \pi^0, p, n, \ldots$$

independentiy of the kind of the secondary. Therefore the single-hadron yield ratios, say π^-/K^-, π^-/p etc., must be the same (at $x \simeq \frac{1}{2}$) for all nuclei in $\pi^- A$ interactions. The theoretical A dependence of V_1^π shown in fig. 15b, can be approximated, for $A > 60$, by

$$V_1^\pi(A) \simeq 1.75\, A^{-0.24}.$$

If the incident particle is a kaon, the production of a fragment containing the strange quark is determined by the probability to absorb the non-strange quark, V_q^K . For instance, for the K^- beam the spectra of strange secondaries $K^-, \bar{K}^0, \Lambda, \Sigma$ etc. must be in the ratio

$$\frac{\frac{1}{\sigma_{prod}^{KA}}\frac{d^2\sigma}{dp\,d\Omega}(K^-A \to h_s X)}{\frac{1}{\sigma_{incl}^{Kp}}\frac{d^2\sigma}{dp\,d\Omega}(K^-p \to h_s X)} = V_q^K(A)\left(1+\frac{\sigma_s}{\sigma_q}\right), \qquad h_s = K^-, \Lambda, \Sigma, \ldots$$

According to fig. 15b, $V_q^K(A) \simeq 0{,}82A^{-0.15}$ for $A > 30$.

On the other hand, the spectra ratio of the non-strange fragments like $\pi^0, \pi^-, \bar{N}$ etc., is determined by the probability to absorb the strange quark:

$$\frac{\frac{1}{\sigma_{prod}^{KA}}\frac{d^2\sigma}{dp\,d\Omega}(K^-A \to h\, X)}{\frac{1}{\sigma_{incl}^{Kp}}\frac{d^2\sigma}{dp\,d\Omega}(K^-p \to h X)} = V_s^K(A)\left(1+\frac{\sigma_q}{\sigma_s}\right), \quad h = \pi^-, \pi^0, \bar{p}, \bar{n}, \ldots$$

For $A > 30$, $V_s^K(A) \simeq 0{,}6\, A^{-0.21}$. Therefore the ratios $\pi^-/K^-, \bar{p}/\Lambda$ etc., are predicted to decrease slightly in the K^-A collisions, as $V_s^K(A)/V_q^K(A) \sim A^{-0{,}06}$. It means that, to some extent, a nucleus works like a filter detaining more non-strange quarks than the strange ones.

In a case of the hyperon beam (Λ or Σ) the multiplicity ratio for the baryons near $x = \frac{2}{3}$ containing the strange quark, is again determined by the probability of absorbing a non-strange quark, say $V_{1q}^{\Lambda}(A)$. On the other hand, a similar ratio for the non-strange baryons is $V_{1s}^{\Lambda}(A)$. As it can be seen , the difference in the A dependences of these quantities is very small.

Experimental observation of the predicted decrease with A of the multiplicity ratio for the non-strange and strange hadrons near $x = \frac{1}{2}$ in the case of a kaon beam would be a check of the hypothesis of the small cross section for a strange quark interacting with a nucleon.

In the hadron-nucleus interaction processes one can, similarly to the hadron-hadron interactions, observe the production of fast secondary hadrons. Due to the mechanism of the interaction we spoke about, we have to consider those cases, when one or two constituents of the incident baryon ($x \sim \frac{2}{3}$ and $x \sim \frac{1}{3}$, respectively) and one constituent of the incident meson $(x \sim \frac{1}{2})$ participate in the interaction. For the baryon-nucleus collision we have, using the expressions (5) and (6):

$$
\begin{aligned}
&V_1^b(A)(q_i q_j + q,\bar{q}\text{-sea}) + V_2^b(A)(q_i + q,\bar{q}\text{-sea}) \longrightarrow \\
&\longrightarrow V_1^b\left(\tfrac{1}{2}B_{ij} + \tfrac{1}{12}(B_i + B_j) + \tfrac{5}{12}(M_i + M_j)\right) + \\
&+ V_2^b\left(\tfrac{1}{3}B_i + \tfrac{2}{3}M_i\right)
\end{aligned} \tag{34}
$$

Besides, some distribution functions have to be introduced: $f_{ij}(x, p_\perp^2)$ for B_{ij}, $f_i(x, p_\perp^2)$ for B_i and $\varphi_i(x, p_\perp^2)$ for M_i . We consider $f_{uu} = f_{ud} = f_{dd}$; $\varphi_u = \varphi_d$, $f_u = f_d$. Instead of (34) we have then

$$
\begin{aligned}
&V_1^b(A)\left[\tfrac{1}{2} f_{ij}(x) B_{ij} + \tfrac{1}{12}\left(B_i f_i(x) + B_j f_j(x)\right) + \tfrac{5}{12}\left(M_i \varphi_i(x) + M_j \varphi_j(x)\right)\right] + \\
&+ V_2^b(A)\left(\tfrac{1}{3} f_i(x) B_i + \tfrac{2}{3}\varphi_i(x) M_i\right)
\end{aligned} \tag{35}
$$

The meson-nucleus collision can be described as:

$$V_1^m(A)(q_i + q_i\bar{q} - sea) \rightarrow V_1^m(A)\left(\tfrac{1}{3}B_i + \tfrac{2}{3}M_i\right) \rightarrow$$

$$\rightarrow V_1^m(A)\left(\tfrac{1}{3}f_i(x)B_i + \tfrac{2}{3}\varphi_i(x)M_i\right) \tag{36}$$

Similarly to the hadron-hadron collision case, one can easily get the secondary particles produced in pA, ΛA, ΣA, πA etc. processes. The calculations are not completed yet: to be in a position to compare the results with experiment, the decays of resonances in different nuclei have to be investigated.

Concluding remarks

There are several theoretical and experimental questions left open in this approach. The situation now is the following. The spectator mechanism is proved by different theoretical and experimental results. The data on the production of secondary mesons support the assumption of quark combinatorics due to which secondary particles are produced in SU(6)-multiplets. The main contribution is given by the lowest multiplets with L=0 (60-70%) and L=1 (20-30%); the presence of the multiplet with L=2 can possibly be about 10%.

The baryon production can be described roughly by the hypothesis of the dominance of the lowest (L=0) SU(6) baryon multiplet: the 56-plet with $J^P = 1/2^+, 3/2^+$. If the devitations of the predictions concerning the relations and Σ^*/Σ from the experimental data are due to the production of the 70-plet (L=1), then the latter is to be expected about 30%.

The experimental increase on the baryon multiplicities with the increase of the energy is somewhat slower than the predicted one. This means, that at the available at present energies the relation (4) is not fulfilled: the proportion of produced meson states is more than 6. Excluding the question of whether the considered energies are asymptotic ones, we see the following possible reasons for the production of more mesons:

a) a considerable contribution of gluonium states decaying mainly into mesons. The production of these states increases the number of meson states in the central region almost not changing the particle production in the fragmentational region.

b) the existence of correlations between quarks of the multiperipherical ladder such as colour correlators or correlations between quarks and quarks or quarks and antiquarks. Such correlations can lead to the suppression of baryon production in the central region which changes the proportions of baryons with different quantum numbers in the fragmentation region.

It would be very interesting to restore the spectra of the directly produced secondaries and try to obtain the distribution of the constituent quarks. The latter would give a possibility to investigate the dinamics of the process.

An important role play the investigations of hadron-nucleus interactions. One can hope to obtain here the hadron distribution in x and $p_{\perp}$ considering the processes when two and one of the constituens quarks transfer into hadrons.

The mentioned theoretical possibilities and experimental questions demand a better theoretical understanding and futher detailed experimental proofs. We hope, that investigations in the not too far future will give the answers.

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$h_{M(0)}$		$L=0$						$h_{M(1)}$				$L=1$					
$J=0$	$J=1$	$\mu_h^0(u)$	$\mu_h^0(d)$	$\mu_h^0(s)$	μ_h^0	$\mu_h^0(\pi^+)$	$\mu_h^0(K^+)$	$J=0$	$J=1$		$J=2$	$\mu_h^1(u)$	$\mu_h^1(d)$	$\mu_h^1(s)$	μ_h^1	$\mu_h^1(\pi^+)$	$\mu_h^1(K^+)$
π^+	ρ^+	$\frac{n_f^J}{8}$	—	—	$\frac{n^J}{16}$	$\frac{2J+1}{4}$	—	δ^+	A_1^+	B^+	A_2^+	$\frac{n_f^J}{24}$	—	—	$\frac{n^J}{48}$	$\frac{2J+1}{12}$	—
π^0	ρ^0	$\frac{n_f^J}{16}$	$\frac{n_f^J}{16}$	—	$\frac{n^J}{16}$	—	—	δ^0	A_1^0	B^0	A_2^0	$\frac{n_f^J}{48}$	$\frac{n_f^J}{48}$	—	$\frac{n^J}{48}$	—	—
π^-	ρ^-	—	$\frac{n_f^J}{8}$	—	$\frac{n^J}{16}$	—	—	δ^-	A_1^-	B^-	A_2^-	—	$\frac{n_f^J}{24}$	—	$\frac{n^J}{48}$	—	—
K^+	K^{*+}	$\frac{n_f^J}{8}\lambda_f$	—	—	$\frac{n^J}{16}\lambda$	—	$\frac{2J+1}{4}$	$\varkappa^+$	Q_1^+	Q_2^+	K^{**+}	$\frac{n_f^J}{24}\lambda_f$	—	—	$\frac{n^J}{48}\lambda$	—	$\frac{2J+1}{12}$
K^0	K^{*0}	—	$\frac{n_f^J}{8}\lambda_f$	—	$\frac{n^J}{16}\lambda$	—	—	$\varkappa^0$	Q_1^0	Q_2^0	K^{**0}	—	$\frac{n_f^J}{24}\lambda_f$	—	$\frac{n^J}{48}\lambda$	—	—
$\overline{K^0}$	$\overline{K^{*0}}$	—	—	$\frac{n_f^J}{8}\lambda_f$	$\frac{n^J}{16}\lambda$	—	—	$\overline{\varkappa^0}$	$\overline{Q_1^0}$	$\overline{Q_2^0}$	$\overline{K^{**0}}$	—	—	$\frac{n_f^J}{24}\lambda_f$	$\frac{n^J}{48}\lambda$	—	—
K^-	K^{*-}	—	—	$\frac{n_f^J}{8}\lambda_f$	$\frac{n^J}{16}\lambda$	—	—	$\varkappa^-$	Q_1^-	Q_2^-	K^{**-}	—	—	$\frac{n_f^J}{24}\lambda_f$	$\frac{n^J}{48}\lambda$	—	—
	ω	$\frac{n_f^J}{16}$	$\frac{n_f^J}{16}$	—	$\frac{n^J}{16}$	—	—	ε	D	?	f	$\frac{n_f^J}{48}$	$\frac{n_f^J}{48}$	—	$\frac{n^J}{48}$	—	—
	ϕ	—	—	$\frac{n_f^J}{8}\lambda_f$	$\frac{n^J}{16}\lambda^2$	—	—	S	?	?	f'	—	—	$\frac{n_f^J}{48}\lambda_f$	$\frac{n^J}{48}\lambda^2$	—	—
η		$\frac{n_f^J}{48}$	$\frac{n_f^J}{48}$	$\frac{n_f^J}{24}\lambda_f$	$\frac{n^J}{48}(1+2\lambda^2)$	—	—										
η'		$\frac{n_f^J}{24}$	$\frac{n_f^J}{24}$	$\frac{n_f^J}{12}\lambda_f$	$\frac{n^J}{48}(2+\lambda^2)$	—	—										

Expansions of $M_J(L)$, $M_i(L)$ and $M(L)$ in terms of real meson states. The normalization coefficients n_f^J and n^J are: $n_f^J=(1+\lambda_f/2)^{-1}(2J+1)$, $n^J=(1+\lambda/2)^{-1}(2J+1)$. The mixing of singlet and octet states in η and η' is not taken into account: $\eta=\eta_1$, $\eta'=\eta_8$. It is assumed, that the states ω, ε, D and f consist of only non-strange quarks while the states ϕ, S, f' only of strange ones.

Table 1

	B_{ij}								B_i			B	B^*_{ijk}			
h_B	$\beta_h(uu)$	$\beta_h(ud)_1$	$\beta_h(ud)_p$	$\beta_h(ud)_\Lambda$	$\beta_h(us)_1$	$\beta_h(us)_0$	$\beta_h(us)_\Sigma$	$\beta_h(ss)$	$\beta_h(u)$	$\beta_h(d)$	$\beta_h(s)$	β_h	$\beta_h(p)$	$\beta_h(\Lambda)$	$\beta_h(\Sigma^+)$	$\beta_h(\Xi^-)$
p	$\frac{1}{9}n_{qq}$	$\frac{1}{18}n_{qq}$	$\frac{41}{90}n_{qq}$	$\frac{1}{2}n_{qq}$					$\frac{2}{15}n_q$	$\frac{1}{15}n_q$		$\frac{1}{10}n_0$	$\frac{17}{27}$			
n		$\frac{1}{18}n_{qq}$	$\frac{41}{90}n_{qq}$	$\frac{1}{2}n_{qq}$					$\frac{1}{15}n_q$	$\frac{2}{15}n_q$		$\frac{1}{10}n_0$				
Λ			$\frac{3\lambda_f}{10}n_{qq}$	$\frac{\lambda_f}{3}n_{qq}$	$\frac{1}{10}n_{qs}$	$\frac{1}{10}n_{qs}$	$\frac{1}{10}n_{qs}$		$\frac{\lambda_f}{15}n_q$	$\frac{\lambda_f}{15}n_q$	$\frac{1}{10}n_s$	$\frac{\lambda}{10}n_0$		$\frac{2\zeta+1}{2(2+\zeta)}$		
Σ^+	$\frac{\lambda_f}{9}n_{qq}$				$\frac{1}{15}n_{qs}$	$\frac{1}{3}n_{qs}$	$\frac{41}{75}n_{qs}$		$\frac{2\lambda_f}{15}n_q$		$\frac{1}{10}n_s$	$\frac{\lambda}{10}n_0$			$\frac{42+9\zeta}{27(2+\zeta)}$	
Σ^0		$\frac{\lambda_f}{9}n_{qq}$	$\frac{\lambda_f}{90}n_{qq}$		$\frac{1}{30}n_{qs}$	$\frac{1}{6}n_{qs}$	$\frac{41}{150}n_{qs}$		$\frac{\lambda_f}{15}n_q$	$\frac{\lambda_f}{15}n_q$	$\frac{1}{10}n_s$	$\frac{\lambda}{10}n_0$		$\frac{1}{2(2+\zeta)}$		
Σ^-										$\frac{2\lambda_f}{15}n_q$	$\frac{1}{10}n_s$	$\frac{\lambda}{10}n_0$				
Ξ^0					$\frac{\lambda_f}{15}n_{qs}$	$\frac{\lambda_f}{3}n_{qs}$	$\frac{41\lambda_f}{75}n_{qs}$	$\frac{1}{6}n_{ss}$	$\frac{1}{15}\lambda_f^2 n_q$		$\frac{\lambda_f}{5}n_s$	$\frac{\lambda^2}{10}n_0$				
Ξ^-								$\frac{1}{6}n_{ss}$		$\frac{\lambda_f^2}{15}n_q$	$\frac{\lambda_f}{5}n_s$	$\frac{\lambda^2}{10}n_0$				$\frac{9+42\zeta}{27(2+\zeta)}$
Δ^{++}	$\frac{2}{3}n_{qq}$								$\frac{2}{5}n_q$			$\frac{1}{5}n_0$				
Δ^+	$\frac{2}{9}n_{qq}$	$\frac{4}{9}n_{qq}$	$\frac{2}{45}n_{qq}$						$\frac{4}{15}n_q$	$\frac{2}{15}n_q$		$\frac{1}{5}n_0$	$\frac{10}{27}$			
Δ^0		$\frac{4}{9}n_{qq}$	$\frac{2}{45}n_{qq}$						$\frac{2}{15}n_q$	$\frac{4}{15}n_q$		$\frac{1}{5}n_0$				
Δ^-										$\frac{2}{5}n_q$		$\frac{1}{5}n_0$				
Σ^{*+}	$\frac{2\lambda_f}{9}n_{qq}$				$\frac{8}{15}n_{qs}$	$\frac{4}{15}n_{qs}$	$\frac{4}{75}n_{qs}$		$\frac{4\lambda_f}{15}n_q$		$\frac{1}{5}n_s$	$\frac{\lambda}{5}n_0$			$\frac{4+6\zeta}{9(2+\zeta)}$	
Σ^{*0}		$\frac{2\lambda_f}{9}n_{qq}$	$\frac{\lambda_f}{45}n_{qq}$		$\frac{4}{15}n_{qs}$	$\frac{2}{15}n_{qs}$	$\frac{2}{75}n_{qs}$		$\frac{2\lambda_f}{15}n_q$	$\frac{2\lambda_f}{15}n_q$	$\frac{1}{5}n_s$	$\frac{\lambda}{5}n_0$		$\frac{1}{2+\zeta}$		
Σ^{*-}										$\frac{4\lambda_f}{15}n_q$	$\frac{1}{5}n_s$	$\frac{\lambda}{5}n_0$				
Ξ^{*0}					$\frac{8\lambda_f}{15}n_{qs}$	$\frac{4\lambda_f}{15}n_{qs}$	$\frac{4\lambda_f}{75}n_{qs}$	$\frac{1}{3}n_{ss}$	$\frac{2\lambda_f^2}{15}n_q$		$\frac{2\lambda_f}{5}n_s$	$\frac{\lambda^2}{5}n_0$				
Ξ^{*-}								$\frac{1}{3}n_{ss}$		$\frac{2\lambda_f^2}{15}n_q$	$\frac{2\lambda_f}{5}n_s$	$\frac{\lambda^2}{5}n_0$				$\frac{6+4\zeta}{9(2+\zeta)}$
Ω^-								$\lambda_f n_{ss}$			$\frac{3\lambda_f^2}{5}n_s$	$\frac{\lambda^3}{5}n_0$				

Expansions of $B^*_{ijk}(L)$, $B_{ij}(L)$ and $B(L)$ in terms of the real baryon states of the 56-plet.

Table 2

	$K^-p \to K^-$ /33/		$K^-p \to \bar{K}^0$ /33/		$K^-p \to K^+$ /33/		$K^-p \to K^0$ /33/		$pp \to K^0_s$ /32/	
	mbarn	%	mbarn	%	mbarn	%	mbarn	%	mbarn	%
$\sigma_{inclusive}$	8,3 ± 1,5	100	8 ± 0,5	100	1,6 ± 0,5	100	1,6 ± 0,5	100	7,4 ± 0,5	100
vector mesons (V)	4 ± 0,4	48	4,2 ± 0,3	53	1,1 ± 0,3	69	0,9 ± 0,2	56	3,4 ± 1	46
tensor mesons (T)	0,9 ± 0,2	11	0,8 ± 0,2	10	0,08 ± 0,01	5	0,08 ± 0,01	5	1,7 ± 0,8	23
mesons with L=0 ($4/3$ V)	5,3 ± 0,5	64	5,6 ± 0,4	71	1,5 ± 0,4	92	1,2 ± 0,3	75	4,5 ± 1,3	61
mesons with L=1 ($12/5 \cdot$ T)	2,2 ± 0,5	25	1,9 ± 0,5	24	0,19 ± 0,02	12	0,19 ± 0,02	12	4,1 ± 1,9	55
mesons with L=2 (estimation)		11		5		–		13		—
mesons with $s_{q\bar{q}} = 1$ (V + $9/5$ T)	5,6 ± 0,4	68 ± ±5	5,6 ± 0,3	71 ± ±4	1,24 ± 0,3	72 ± ±19	1,04 ± 0,2	65 ± ±13	6,5 ± 1,8	87 ± ±24

Table 3. Kaon production in K^-p collisions at 32 GeV/c /33/ and in pp collisions at 4o5 GeV/c /32/. The inclusive cross-section is decreased in comparison with the data of /33/ by the value of the cross-section of the diffraction dissociation.

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